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Design study of a remotely operated repair pod for future Hyperloop systems

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Summary

This report outlines the Liverpool Hyperloop Team conceptual design study for a remotely operated repair pod tailored to the unique operational environment of future Hyperloop transportation systems. The project is motivated by the need for fast, efficient, and autonomous maintenance in high-speed, vacuum-based transit networks, where conventional railway repair strategies are inadequate.

The repair pod is envisioned to operate both with magnetic levitation and mechanical wheel propulsion, ensuring reliability even when the maglev track is compromised. It will feature a backup power system independent of the Hyperloop infrastructure, enabling autonomous travel and towing capability in emergency situations. The pod will be remotely operated, supported by a sophisticated electronics and software architecture for fault detection, monitoring and basic decision-making.

The research focuses on four core areas:

- Maglev and Propulsion Systems: Exploring a hybrid propulsion strategy for reliability and speed. The design goals of the propulsion and levitation system for the pod therefore place focus on the reliability of the system and the ability to function in nonoptimal conditions. A failure in the power transmission to the pod or a compromise in the structural integrity of the tube are critical safety risks. These considerations necessitate a departure from conventional, single-mode propulsion to a hybrid propulsion system that combines the efficiency of magnetic levitation with the dependability of mechanical wheel propulsion. This is accomplished through a primary Linear Reluctance Motor (LRM) drive with EMS-based levitation in combination with a secondary retractable mechanical wheel drive.

- Chassis Structure: The chassis sub team is responsible for outlining the structural framework of the Hyperloop pod. The primary focus is how it will support the subsystems (of the sensors for detecting) whilst withstanding vacuum conditions. The initial planning of how the sensors will be integrated onto the chassis and pod to enable effective system monitoring and data collection has been explored. The focus also includes how the pod will accommodate internal components, and the size required for this integration. In addition to this, preliminary research has considered the aerodynamics of the pod, with an overall aim to minimise drag within the Hyperloop tube environment.

- Vacuum Tube Systems: The vacuum tube team explored to develop techniques to identify and analyse micro-leaks within the Hyperloop tunnel. The primary focus has been on modelling the behaviour of supersonic under-expanded jets, investigating how a high-Mach jet expands into a 100 Pa environment. This involved deriving a generalised relationship between mass flow rate, jet velocity, ambient pressure, and expansion angle to estimate plume radius and axial extent. The research explored how a plume's momentum flux decrease with expansion could be used to define the plume boundary by equating it to ambient pressure. In parallel, the research focused on determining the minimum resolution required by on-board density sensors to capture such plumes at 200 km/h with 30 samplings for reliability.

- Electronics & Software: Designing the "nervous system" for the repair pod. This involves architecting the foundational communication framework, the reliable, redundant data highway inside the tube, and defining the data flow systems that prioritise robotic and other operational commands over high bandwidth video and background logs. Our work takes this communication framework and utilises a digital twin and Augmented Reality to give an operator critical information and enhanced perception needed to perform complex maintenance tasks safely and effectively from a distance.

The methodology includes literature reviews, simulation-based scenario analyses and system design to establish a foundation for future prototyping and development. This report does not aim to provide final solutions but rather builds a framework to guide further technical investigation and system integration in subsequent project phases.

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1. Introduction

The Liverpool Hyperloop Team is a multidisciplinary group of students from the University of Liverpool, driven by a shared motivation for developing sustainable and high-speed transportation solutions. Comprising students studying mechanical engineering, aerospace engineering, computer science, electrical engineering and electronics, the team is structured into specialised sub-groups focusing on Magnetic Levitation, Electronics & Software, Vacuum Tube, and Chassis. This collaborative framework supports the team's core mission: to innovate and contribute to the advancement of Hyperloop technologies within the UK and globally.

This report presents a detailed design study on a remotely operated repair pod for future Hyperloop systems, addressing the critical challenge of performing maintenance and repair operations within the unique constraints of a vacuum-sealed, high-speed transit environment. In conventional railway systems, faults are manually detected and repaired, often causing delays and increased operational costs. However, such an approach is unsuitable for Hyperloop infrastructure, where rapid response times and minimal system disruption are imperative due to the single-track configuration and continuous high-speed operations.

To meet this need, the proposed solution integrates a mobile maintenance pod equipped with a hybrid propulsion mechanism, leveraging magnetic levitation where available, with fallback mechanical wheels when needed. The pod is designed to function independently of the main power system and includes onboard battery power sourced externally through renewable energy sources. Equipped with robotic systems and a remote-controlled interface, the pod can respond to critical faults such as vacuum leaks, structural issues, and debris on the track with minimal human intervention.

The research aims to develop conceptual solutions in four core areas: magnetic levitation and propulsion alternatives, chassis material and structural integrity, vacuum tube pressurisation and HVAC systems, and an electronics and software architecture for fault detection and remote operation. Rather than offering final engineering solutions, the report focuses on identifying failure modes, proposing feasible detection strategies, and laying the groundwork for future development and integration.

This foundational study marks the Liverpool Hyperloop Team’s entry into the European Hyperloop Week competition, demonstrating both a commitment to research excellence and a vision for contributing to the future of high-speed, sustainable transportation.

1.1 Background & Context

The Hyperloop transportation concept has emerged as a revolutionary solution for high-speed, suitable travel. By operating pods with low-pressure tubes using magnetic levitation, the hyperloop system proposes to dramatically reduce travel times while minimising environmental impact. However, the unique vacuum environment and high operational speeds pose significant engineering challenges, particularly in terms of maintenance and repair. Unlike traditional rail systems. Where manual inspection and repair can be performed during scheduled downtime, the Hyperloop’s vacuum-sealed and continuous-use configuration demands innovative solutions to maintain operational safety and efficiency.

In this context, the Liverpool Hyperloop Team has undertaken a conceptual design study for a remotely operated repair pod. The repair pod is envisioned to combine magnetic levitation with mechanical wheel propulsion, ensuring reliable mobility even if the primary maglev system is compromised. To support autonomous fault detection and basic repair operations, the design integrates a range of advanced sensor systems – including lidar for ovalness assessment, and thermal imaging for monitoring cable health. These sensors have been carefully evaluated and calibrated to function reliably at the pod's operational speed of 200 km/h.

Recognising the critical role of structural integrity and aerodynamic performance, the team has also engaged in developing Computer Aided Design (CAD) models of the undercarriage and wheel systems. Finite Element Analysis (FEA) has been considered to verify the strength and durability of these designs within the vacuum environment. Additionally, the use of a robotic arm connected to the pod would need to be investigated, to enable minor repairs along the tube walls, further enhancing the pod's capacity to support Hyperloop system reliability.

The design implementation of a dedicated repair pod also represents uncharted territory in Hyperloop research. Existing literature and prototypes primarily focus on passenger transport and tube construction, with limited consideration for long-term maintenance and system longevity. By addressing this gap, the Liverpool Hyperloop Team's work not only expands the understanding of operational challenges in vacuum-based transit systems but also contributes to the establishment of a safe and efficient maintenance framework. Ultimately, this foundational study has the potential to improve the overall safety, reliability, and economic viability of future hyperloop transportation systems, making them more resilient to operational disruptions and better equipped for widespread deployment.

1.2 Project Aims and Objectives

The primary aim of this project is to develop a comprehensive conceptual design for a remotely operated repair pod, tailored for the unique operational environment of future Hyperloop systems. Recognising the limitations of conventional railway repair practices, the project seeks to create a solution that ensures the safety, reliability, and operational continuity of high-speed, vacuum-based transportation networks.

To achieve this aim, the project established a series of clear and measurable objectives:

- **Develop a hybrid propulsion system** that allows the repair pod to operate efficiently on magnetic levitation tracks while retaining the flexibility to switch to mechanical wheel propulsion in the event of maglev system compromise. This dual-mode operation ensures that the pod remains operational in emergency scenarios, providing reliable access to all sections of the hyperloop infrastructure.
- **Design a robust chassis** that meets structural integrity and aerodynamic stability requirements under vacuum conditions. The chassis will be optimised to endure the extreme environmental demands of the hyperloop tube, ensuring safety and durability at operating speeds up to 200 km/h.
- **Incorporate advanced sensor technologies** to enable precise fault detection and continuous monitoring. This includes a lidar system to assess the ovalness of the vacuum tube, a laser triangulation system for real-time deformation measurement, and a thermal camera for

systematic cable mapping at 20 cm intervals. These sensors have been evaluated and calibrated to function reliably at the pod's operational speed, ensuring accurate data collection without failure.

- **Investigate the feasibility and performance of a robotic arm system** capable of conducting minor repairs along the tube walls, enhancing the pod's ability to respond autonomously to maintenance challenges.
- **Establish electronics and software architecture** that enables remote operation and basic decision-making. The system will be designed to integrate seamlessly with the pod's sensor suite, providing robust control and monitoring functions to support autonomous and operator-directed tasks.
- **Evaluate the overall system performance and operational safety** using scenario-based simulations and risk analyses, such as the Risk Priority Number (RPN) analysis, to validate the concept's effectiveness and identify any remaining limitations or areas for future improvement.

This project does not aim to produce a finalised engineering solution or working prototype but rather to lay the groundwork for future development and integration. By addressing these objectives, the Liverpool Hyperloop Team aims to contribute meaningfully to the ongoing advancement of hyperloop technology and its safe, efficient operation.

1.3 Scope of the Project

This report defines the boundaries and key focus areas of the conceptual repair pod design, identifying critical elements for achieving safe and reliable operation in the Hyperloop environment. The scope of the work includes:

- The development of a hybrid propulsion system, combining magnetic levitation and mechanical wheel mechanisms to ensure continuous mobility even during maglev track failures.
- The creation of a detailed CAD models to form the basis for future structural analysis and refinement.
- The selection and integration of advanced sensors, including lidar, laser triangulation, and thermal imaging, to enable reliable real-time monitoring and fault detection at operational speeds.
- The investigation of a robotic arm concept for performing minor repairs within the vacuum environment.
- The application of scenario-based simulations and risk assessment (such as RPN analysis) to validate the feasibility and safety of the proposed pod concept.
- The design of a redundant, high-bandwidth communication architecture that utilises a 5G network for its low latency and a dissimilar Li-Fi backup system to ensure immunity from electromagnetic interference and guarantee a constant link.
- The development of a tiered data management strategy, which uses specific network protocols (UDP, WebRTC, TCP) to prioritise real-time robotic commands over high-definition video feeds and background system logs, ensuring operational responsiveness.
- Conceptualising an intelligent operations platform, which leverages the communication architecture to power a comprehensive Digital Twin. This includes enabling virtual mission

rehearsals, providing live Augmented Reality (AR) overlays for operators, and facilitating predictive maintenance analysis.

During the conceptual design phase, several unique challenges were encountered. Notably, it is not feasible for the repair pod to travel at the same speed as the passenger pods, given the need for precise detection and repair. The high speeds of passenger pods would compromise the accuracy of sensor measurements and the quality of data capture. Consequently, the sensors – particularly the lidar – had to be calibrated and assessed for reliable operation at a reduced, but still rapid, speed of 200 km/h.

Additionally, to assess the extent of damage or the nature of required repairs, the pod will be fitted with high-resolution cameras capable of providing visual confirmation of identified issues. However, no commercially available camera system can currently deliver clear and reliable images of faults at the speed typical for passenger pods. Therefore, the chose speed of 200 km/h represents a carefully considered compromise to balance rapid inspection capability with sufficient image clarity and data fidelity.

This report does not include detailed manufacturing processes, as it instead aims to define a conceptual framework for future development, offering a foundation that can be expanded upon in subsequent phases and project iterations.

2. Literature Review

2.1 Overview of Hyperloop Technology

The Hyperloop system is a futuristic mode of transportation that aims to achieve high-speed travel by propelling passenger or cargo pods through low-pressure vacuum tubes. The Hyperloop system is designed to drastically reduce travel times between major cities while promoting energy efficiency and sustainability.

The system operates by significantly minimising air resistance and friction through two key mechanisms: the maintenance of a near vacuum environment within the transit tube and the use of magnetic levitation to lift and guide the pods along the track. Propulsion is typically achieved through linear electric motors embedded along the guideway, enabling smooth acceleration and deceleration without direct contact with the track. Pods are expected to travel at speeds exceeding 1000 km/h (Walker, 2018), presenting unique engineering challenges related to aerodynamics, pressure regulation, structural integrity, and system safety. Unlike traditional rail systems, the Hyperloop operates on a single, enclosed route with limited access points, meaning that regular maintenance or emergency repairs cannot be conducted using conventional methods. Additionally, the need to maintain a continuous low-pressure environment within the tube further complicates any intervention, as pressurising the system for human access would result in significant downtime and operational disruption.

The system’s reliance on advanced technologies across multiple engineering disciplines such as high strength lightweight materials, real-time environmental monitoring, backup power systems and remote communication, demands a new approach to infrastructure maintenance and fault response. This research project, which investigates the design of a remotely operated repair pod, directly addresses the limitations of current maintenance practices and contributes to the development of scalable, autonomous solutions suited to the complex environment of a Hyperloop system. As the concept moves closer to real world implementation, maintenance and repair capabilities will play a critical role in ensuring the safety, reliability and long-term viability of the system.

2.2 Propulsion and Levitation Systems

The original Hyperloop concept utilised air bearing suspension in combination with magnetic propulsion in the form of linear induction motors (LIM) with the aim of reducing cost and maximising pod speed. Since then, many proposed Hyperloop systems have based their design around magnetic levitation and propulsion systems due to the proven and mature nature of the technology, having been implemented in maglev train systems around the world (Courtman *et al*., 2023; MIT Hyperloop, 2017; Nøland, 2021). Therefore, an understanding of magnetic levitation and propulsion systems is vital to the design of any Hyperloop system or component.

There are two primary magnetic levitation technologies: electromagnetic suspension (EMS) and electrodynamic suspension (EDS). EMS is based on magnetic attraction forces between the guideway and the vehicle. Onboard electromagnets are suspended below a magnetic rail (Fig. 1). The magnetic attraction force is inversely proportional to the separation; therefore, a small air gap in the range of ±10 mm and precise air gap control is necessary to maintain stability (Lee, Kim and Lee, 2006). The stability issue becomes especially pronounced at high speeds. The main benefits of EMS is that it is a proven and commercially available technology and does not need wheels as it can achieve levitation at zero or low speeds. However, it is inherently unstable so the air gap separation must be closely monitored and controlled, and the track must be manufactured to a relatively high tolerance.

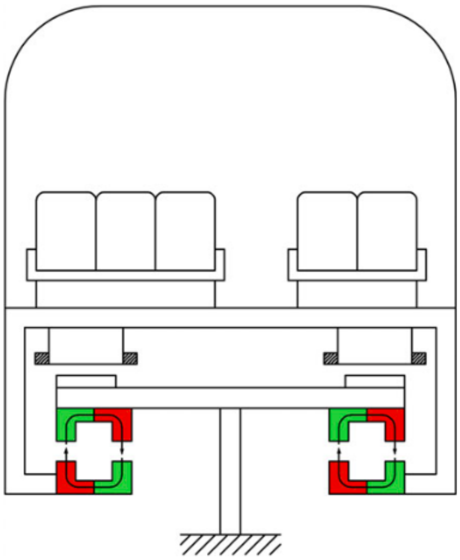

Figure 1: Electromagnetic suspension (EMS) configuration (Han and Kim, 2016).

EDS is, in contrast with EMS, based on the magnetic repulsive force. On-board magnets induce Eddy currents on a conducting guideway generating a magnetic field and levitating the vehicle (Fig. 2). EDS is very stable and essentially self-regulating, allowing for an air gap of up to 100 mm and eliminating the need for air gap control (Lee, Kim and Lee, 2006). However, currents are only induced when the vehicle is in motion so it cannot levitate at low or zero speeds, necessitating onboard wheels below the levitation threshold speed. It also entails stronger magnetic field strengths, which may lead to a need for magnetic shielding for passengers. EDS may be implemented with permanent magnets, electromagnets, or superconducting magnets.

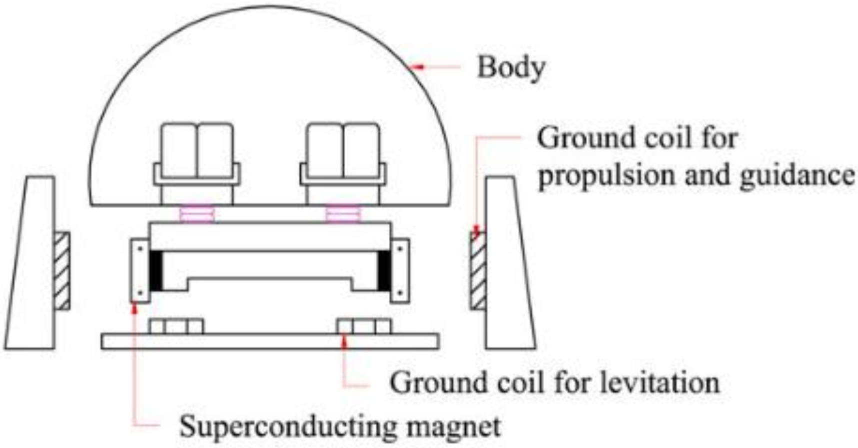

Figure 2: EDS configuration for the MLU-001 (Han and Kim, 2016).

Superconducting magnets may be used with either EMS or EDS technologies. The main benefits of superconducting magnets are that they create strong magnetic fields, allowing for larger air gaps; can achieve stable levitation due to the Meissner effect; are suitable for high load capacity situations; and have reduced drag and friction, especially at higher speeds (Wang and Wang, 2017). However, the cooling required to maintain superconductivity entails higher energy consumption, as well as more complex designs to accommodate the additional components.

The two primary magnetic propulsion technologies are linear induction motors (LIM) and linear synchronous motors (LSM). In a LIM, the primary creates space-time variant magnetic fields which induces an electromotive force in the secondary, a conducting sheet (Fig. 3) (Lee, Kim and Lee, 2006). LIMs are relatively simple and robust and are easily controlled. There are two types; Long Primary (LP) type, where the stator coils are on the guideway and the conducting sheet is on the vehicle, and Short Primary (SP) type, where the stator coils are onboard while the guideway consists of a conducting sheet. SP LIMs have lower construction costs due to the simpler guideway design but suffer from lower energy efficiency and higher drag force due to the magnetic end effect. This makes them unsuitable for high-speed operation. LP LIMs have higher construction costs but can achieve higher speeds.

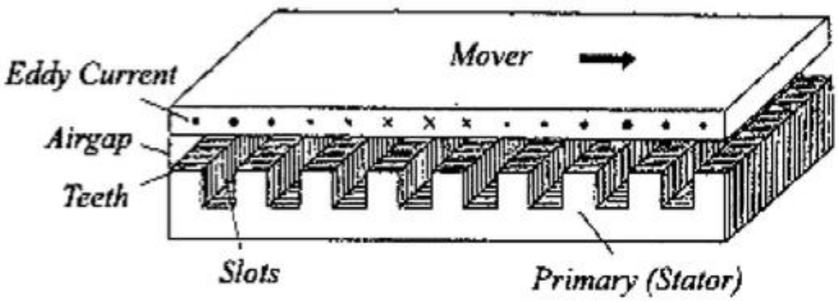

Figure 3: Long primary (LP) type linear induction motor (Lee, Kim and Lee, 2006).

LSM's rely on a primary generating a magnetic field, just like LIMs. However, in LSMs, the secondary also consists of permanent magnets or electromagnets as opposed to a conducting sheet (Fig. 4). The placement of the magnets on the secondary ensures that the motion is synchronised with the magnetic field, leading to zero slip and higher efficiency. However, this requires more complex control systems to maintain synchronisation and therefore higher cost. Just as in LIMs, there are Short Primary (SP) and Long Primary (LP) types of LSMs.

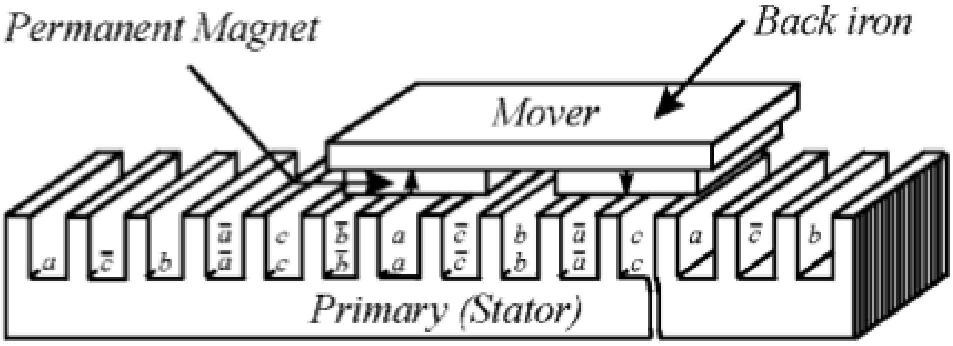

Figure 4: Configuration of an LP type LSM (Lee, Kim and Lee, 2006).

An electrodynamic wheel system (EDW) consists of a radially positioned Halbach array that is rotated above a flat conductive guideway (Fig. 5) (Bird and Lipo, 2005). The benefit of such a system is that it can provide levitation, guidance, and thrust simultaneously. It also reduces power consumption and costs due to the use of permanent magnets and the lack of a need for side walls for guidance. In addition, by using several wheels in series reinforcing effects can be created which lead to higher forces.

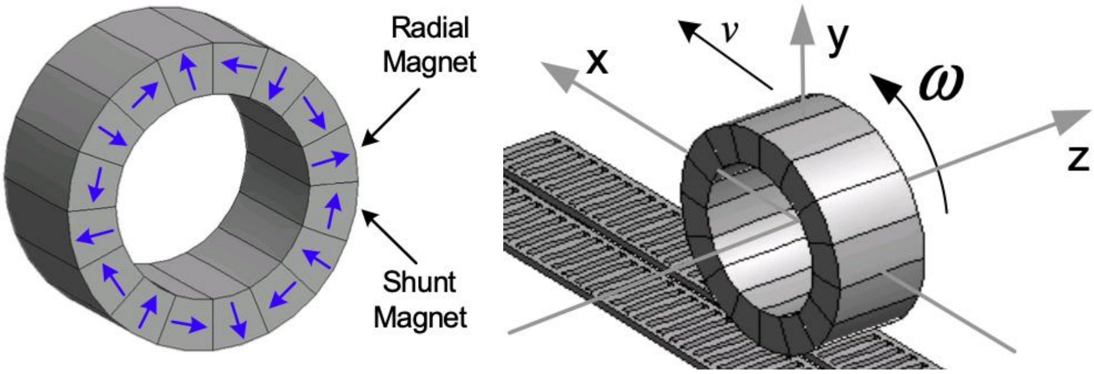

Figure 5: Permanent magnet Halbach array electrodynamic wheel (Bird and Lipo, 2005).

A Linear Reluctance Motor (LRM) operates on the principle that a magnetic circuit will act to minimize its reluctance. In such a propulsion system, the primary mover on the vehicle consists of electromagnets with a ferromagnetic core, while the secondary on the guideway is composed of a passive, magnetically permeable material (Boldea and Nasar, 1997). Propulsion is generated by sequentially energizing the onboard electromagnetic, creating a travelling magnetic field that attracts and pulls the secondary elements on the guideway into alignment, thereby producing a thrust force. The advantage of an LRM is the cost-effectiveness and robustness of the passive track. However, this comes at the cost of lower force density. Overall, the inherent simplicity of LRMs make them a compelling choice when the reliability of the system is a key consideration.

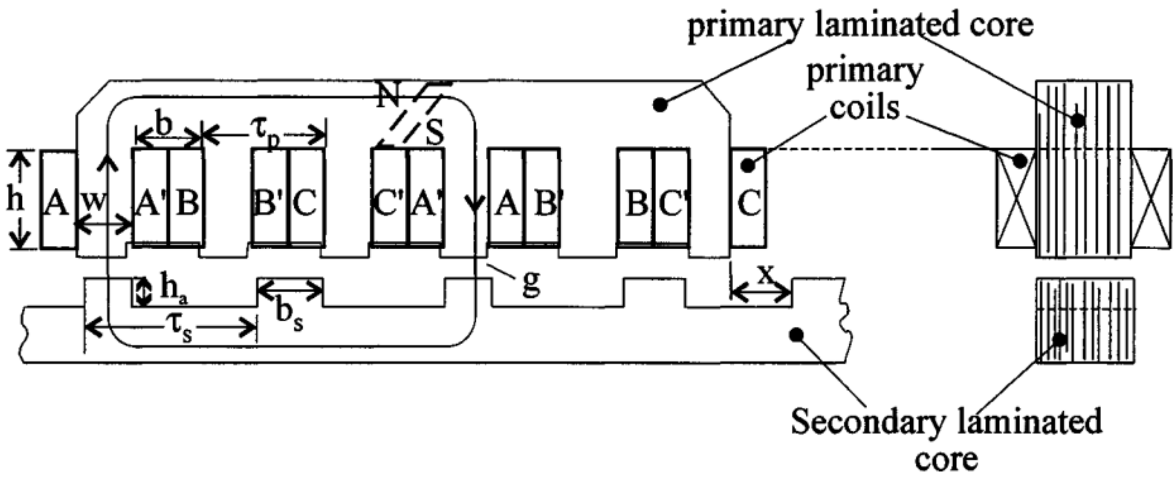

Figure 6: Configuration of a single-sided flat three-phase LRM (Boldea and Nasar, 1997).

The propulsion methods mentioned can be operated in reverse to achieve braking. This can also be regenerative in nature, recovering kinetic energy and improving energy efficiency. This may be supplemented by aerodynamic braking or a mechanical braking system for use in emergencies.

2.3 Tube and Pod Design Concepts

Thorough safety practices are imperative for the future commercialisation of Hyperloop. When Nishimoto and Kezirian (2023) applied NASA human spaceflight safety practices to the hyperloop, multiple areas of failure were highlighted. Two key preliminary safety hazards for the tunnel included structural integrity compromise of the tunnel and pod collision. The reason for the former was identified as rapid re-pressurisation of the tube resulting from pressure system failure, while pod derailment was the most likely cause for the latter.

A similar study, "Safety by Design - Hyperloop," conducted by students at the University of Twente under supervision (2021), discusses the risks involved in a hyperloop system. This study assigned a Risk Priority Number (RPN) based on risk analysis and identified structural failure as the most critical. Another significant risk identified by this study was the failure of power transmission to the pod, which could compromise the pod's ability to decelerate. Lastly, improper lane switching, which can lead to derailment, was identified as a critical safety hazard. This hazard is directly related to the malfunctioning magnetic field strength of the maglev guideways.

A hyperloop tunnel could be considered a pressure vessel, as it would be designed to maintain a pressure differential with low pressure on the inside. In such a design, ductile fracture, ratchet, fatigue and buckling are assumed to be the dominant failure modes, based on ASME Section III (Miya et al., 1998). It is worth noting that for such high-speed transportation, only safe and specialised construction materials are likely to be used, for example, the Specialised Steel by the POSCO Group, whose material properties are disclosed (POSCO Group Newsroom, 2024). Such specialised steel is expected to have enhanced material properties than traditional steel. Thus, creep effects on the integrity of the vacuum tube can be considered negligible, as the operational temperature remains well below 200 °C.

However, the tunnel wall will experience thermal variations due to the ambient outside temperature and the controlled temperature on the inside. Additionally, each passing pod will start a new thermal cycle within the tube. In a study on the aftershock effects of a hyperloop pod passing through the tube, Mrazek et al. (2023) estimated a rise of 26.5 K in the tube wall temperature each time a pod passes, travelling beyond the Kantrowitz limit.

Based on these conditions, the key failure mode is a ductile fracture resulting from the pressure differential, cyclic thermal stresses due to external and internal temperature variations, and cyclic electromagnetic (EM) forces from the magnetic levitation system. Additionally, the risk of structural buckling in the vacuum tube walls must be mitigated. The nature of these forces will induce tensile and sheer stresses in the tube.

In the domain of structural engineering, ductile fractures are more likely to occur at weaker locations. A cylindrical design for tubes is the primary choice to avoid stress concentrations. Therefore, in such applications, welded joints are often identified as the weaker locations due to possible Heat Affected Zones (HAZs), porosity, and material mismatches. As described by Wang, Tong and Shi (2025), welded joints in steel are considered weak parts due to complex stress conditions and are susceptible to failure by ductile fracture. Ductile fractures are characterised by necking of the material due to excessive plastic deformation.

Inferring from the reviewed literature and assuming a stringent quality control regime during Hyperloop construction, one critical pathway linking vacuum tube to pressure system failure is the presence of micro-leaks within the tube. These micro-leaks place continuous demand on the vacuum pumps, leading to overuse and mechanical wear of system components. If not addressed through timely maintenance, this degradation can culminate in system failure. The Health and Safety Executive (2024) highlights poor maintenance as a recurring cause of pressure system failure. The most probable locations for micro-leaks are at dynamic interfaces, particularly airlock seals and seal seatings.

On the other hand, asymmetry in the magnetic field strength of the maglev guideway and power transmission failures to the pod may arise from inconsistencies in electrical current supply. Based on Ohm's Law, $V = IR$, a decrease in current at a given voltage is influenced by an increase in resistance in the system. This would also increase the local temperature, associated with resistive heating, IR^2. Contrary to open transmission line failures where corrosion, loose connections, and environmental factors are the primary culprits, such a failure in a controlled environment of hyperloop system can be narrowed down to loose connections.

Lastly, both plastic deformations leading to ductile fracture and structural buckling will have a direct impact on the geometry of the tube. While ductile fracture anticipated around welded joints is typically preceded by localised necking and gradual thinning, buckling will result in a sudden lateral displacement and deviation from the original geometric configuration of the tube.

Therefore, the diagnostic pod must be capable of detecting micro-leaks within the vacuum tube, identifying asymmetries in maglev guideway magnetic strength, monitoring thermal anomalies in power transmission systems, measuring the tube wall curvature, and measuring the tube wall thickness along the welded joint.

Measurement tools such as magnetometers (to assess guideway magnetic strength), LiDAR sensors based on Time-of-Flight principles (to map wall curvature), thermal cameras (to monitor thermal anomalies in power transmission lines), and ultrasonic sensors (to evaluate wall thickness) have been widely adopted in both railway and aerospace applications. These tools can therefore be confidently integrated into the diagnostic pod at strategically chosen locations. However, the methodology for leak detection warrants further investigation to identify the most effective sensing approach. Although Acoustic Imaging Cameras (AICs) have gained popularity due to their high accuracy in pinpointing leaks, their limited coverage area presents a challenge for high-speed diagnostics. As such, AICs should be supplemented by tools capable of approximating leak locations while the pod moves at a high speed, eventually narrowing the area to enable the AIC to precisely localise the leak when the pod is stationary.

2.4 Operational and Safety considerations

Thorough safety practices are imperative for the future commercialisation of Hyperloop. Studies applying safety practices from domains like NASA human spaceflight to Hyperloop have highlighted several areas of potential failure. Two key preliminary safety hazards identified for the tunnel are the structural integrity compromise of the tunnel and the potential for pod collision. The primary cause for the former was noted as rapid re-pressurisation of the tube following a pressure system failure, while pod derailment was the most likely reason for the latter.

A "Safety by Design - Hyperloop" study assigned a Risk Priority Number (RPN) to various risks and identified structural failure as the most critical. Another significant risk was the failure of power transmission to the pod, which could impede its ability to decelerate. Improper lane switching, a potential cause of derailment, was also flagged as a critical safety hazard and is directly linked to the malfunctioning magnetic field strength of the maglev guideways.

A hyperloop tunnel can be considered a pressure vessel, designed to maintain a low internal pressure. Consequently, the dominant failure modes are assumed to be ductile fracture, ratchet, fatigue, and buckling. Given the controlled environment, failures are likely to stem from loose connections rather than environmental factors. These issues can impact the geometry of the tube through plastic deformations leading to ductile fractures and structural buckling. Therefore, a diagnostic pod must have the capability to detect micro-leaks, identify asymmetries in the maglev guideway's magnetic strength, monitor for thermal anomalies in power transmission systems, and measure both the tube wall curvature and thickness, particularly around welded joints.

3. Methodology

3.1 Design Approach and Framework

3.1.1 Leak Detection System

Any leak involves fluid movement, and leveraging the understanding of their behaviour and properties will fulfil the objectives of detection. A leak can be quantified using the Converging-Diverging nozzle implications.

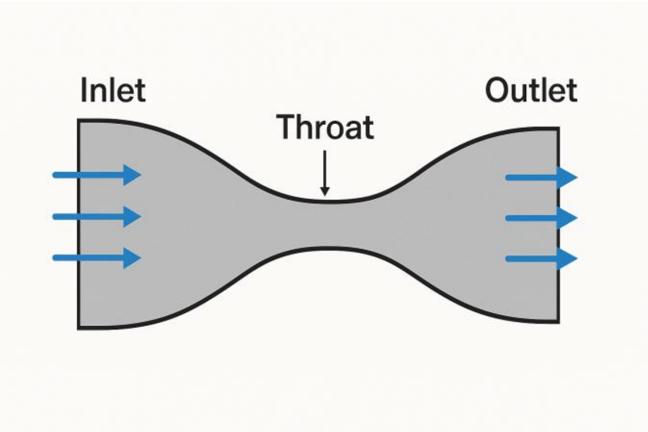

Figure 7: Converging-Diverging nozzle, with inlet, throat and outlet (labelled)

Here, Throat is considered as the leak location, Inlet is the ambient atmosphere, while the Outlet is the inside of the vacuum tube.

Given the larger pressure differential between the outside and the inside of the tube, the Pressure Ratio (PR) is expected to be lower than the Critical Pressure Ratio (P_{CR}) of air, which is 0.528.

$$PR = \frac{P_{ds}}{P_{us}}$$

Where,

Abbreviation	Definition
PR	Pressure Ratio
P_{ds}	Downstream Pressure: Pressure after the throat (Pressure in the tube)
P_{us}	Upstream Pressure: Pressure before the throat (Atmospheric pressure)

$$\Rightarrow \quad PR = \frac{100}{101325} = \mathbf{9.87 * 10^{-4}}$$

Here, $PR < P_{CR}$. In scenarios where the PR of the fluid is equal to or smaller than its P_{CR}, the choke flow is attained at the throat. Choke flow is the condition where the speed of fluid equals the speed of sound, giving a Mach Number, M = 1.

Implementing an isentropic relationship, the fluid temperature, pressure, and density at the throat can be calculated using the equations:

$$\frac{T}{T_{out}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1}$$

$$\frac{P}{P_{out}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma-1}}$$

$$\frac{\rho}{\rho_{out}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{1}{\gamma-1}}$$

Where,

Abbreviation	Definition
T	Temperature at the throat (K)
T_t	Temperature outside the throat (K)
P	Pressure at the throat (Pa)
P_t	Pressure outside the throat (Pa)
ρ	Density at the throat (kg/m^3)
ρ_t	Density outside the throat (kg/m^3)
γ	Fluid specific heat ratio (1.4 for air)
M	Mach Number at the throat

Here, outside the throat is regarded as the position of air in the ambient atmosphere. Normal Temperature and Pressure (NTP) will be used to determine the fluid properties at the throat.

The properties of air at NTP outside the throat are as follows:

$T_t = 293.15\ K$

$P_t = 101325\ Pa$

$\rho_t = 1.204\ kg/m^3$

Rearranging the equations to solve for the fluid temperature, pressure, and density at the throat gives:

$$T = 293.15 * \left(1 + \frac{1.4 - 1}{2} 1^2\right)^{-1} = \mathbf{244.29\ K}$$

$$P = 101325 * \left(1 + \frac{1.4 - 1}{2} 1^2\right)^{-\frac{1.4}{1.4-1}} = \mathbf{53528.15\ Pa}$$

$$\rho = 1.204 * \left(1 + \frac{1.4 - 1}{2} 1^2\right)^{-\frac{1}{1.4-1}} = \mathbf{0.76\ kg/m^3}$$

Air velocity at the throat, U, can be calculated as:

$$U = \sqrt{\gamma R T}$$

$$U = \sqrt{1.4 * 287 * 244.29} = \mathbf{313.29\ m/s}$$

The following are the air properties at the leak entrance in the vacuum tube. The air will undergo rapid expansion as it enters the tube at 100 Pa and will attain a supersonic speed. The Mach Number as the air expands in the tube, M_{exp}, can be calculated by rearranging the isentropic pressure relation, which gives:

$$M_{exp} = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P}{P_t}\right)^{-\frac{\gamma-1}{\gamma}} - 1\right]}$$

Where,

Abbreviation	Definition
P	Pressure inside the tube (Pa)
P_t	Pressure at the throat (Pa)
M_{exp}	Mach Number as the air expands inside the tube

$$M_{exp} = \sqrt{\frac{2}{1.4 - 1}\left[\left(\frac{100}{53528.15}\right)^{-\frac{1.4-1}{1.4}} - 1\right]} = \mathbf{5.01}$$

Using the Mach Number air attains as it expands inside the tunnel, its temperature and density can be calculated using the isentropic relations. Additionally,

$$T_{exp} = 244.29 * \left(1 + \frac{1.4 - 1}{2} * 5.01^2\right)^{-1} = \mathbf{40.58\ K}$$

$$\rho_{exp} = 0.76 * \left(1 + \frac{1.4 - 1}{2} * 5.01^2\right)^{-\frac{1}{1.4-1}} = \mathbf{8.55 * 10^{-3}\ kg/m^3}$$

The following would have been the air properties throughout its expansion if the vacuum tube did not have pre-existing air in controlled environment. However, with pre-existing air in the tube, the under-expanded air will undergo rapid mixing. To determine the approximation of temperature and density at close proximity of the leak, the properties of tube air must be known. While the temperature of the air inside the tube, T_{tube}, is maintained at 285.65K, its density, ρ_{tube}, can be calculated as:

$$\rho_{tube} = \frac{P_{tube}}{RT_{tube}}$$

$$\rho_{tube} = \frac{100}{287 * 285.65} = \mathbf{1.22 * 10^{-3} kg/m^3}$$

Expansion velocity, U_{exp}, can be calculated as:

$$U_{exp} = M_{exp} * \sqrt{\gamma R T_{exp}}$$

$$U_{exp} = 5.01 * \sqrt{1.4 * 287 * 40.58} = \mathbf{639.73\ m/s}$$

	Throat Air Properties	**Under-Expansion Air Properties**	**Vacuum Tube Air Properties**
Velocity	313.29 m/s	639.73 m/s	0 m/s (assumed)
Temperature	244.29 K	40.58 K	285.65 K
Density	0.76 kg/m^3	$8.55 * 10^{-3} kg/m^3$	$1.22 * 10^{-3} kg/m^3$

The jet expansion angle, θ, can be calculated using the Prandtl–Meyer turning angle:

$$\theta = \nu(M_2) - \nu(M_1)$$

Where,

ν is the Prandtl–Meyer function, expressed as:

$$\nu(M) = \sqrt{\frac{\gamma+1}{\gamma-1}} * tan^{-1}\left(\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)}\right) - tan^{-1}\left(\sqrt{M^2-1}\right)$$

Since $M_1 = 1, \nu(M_1) = 0$

$$\nu(M_2) = \sqrt{\frac{2.4}{0.4}} * tan^{-1}\left(\sqrt{\frac{0.4}{2.4}(5.01^2-1)}\right) - tan^{-1}\left(\sqrt{5.01^2-1}\right)$$

$$\nu(M_2) = \mathbf{1.34\ rads\ or\ 76.78°}$$

Therefore, the jet expansion angle of the leak is:

$$\theta = 76.78° - 0° = \mathbf{76.78°}$$

The influence of the existing air in the tube will have negligible effect on the expansion angle since the jet density momentum of the under expanded jet will be several folds greater, since the fluid velocity inside the tunnel is assumed to be 0 m/s.

Each property calculated until now is independent of the leak size. An analytical solution for detectable jet plume can be derived which will be crucial in selecting the desired resolution of the detection sensor.

Momentum flux, ρU^2, which is defined as the rate of momentum carried per unit area, is a critical factor in deriving the jet plume size. The leak jet will form a cone shaped plume whose axial distance from the exit is the position where the plume stops growing. This position is reached when:

$$\rho U^2 = P_{tube}$$

Alternatively, the above equation can be written using mass flow rate as:

$$\dot{m} = \rho A U$$

Rearranging the mass flow rate equation for ρ gives:

$$\rho = \frac{\dot{m}}{AU}$$

This gives:

$$\frac{\dot{m} * U}{A} = P_{tube}$$

Here, A, is the cross-sectional area of the plume. Therefore, the final equation of position when the plume stops growing can be given as:

$$\frac{\dot{m} * U_{exp}}{A_{plume}} = P_{tube}$$

Where A_{plume} is the cross-sectional area of the plume.

The radius of the plume, r, is the trigonometric function of its axial distance from the leak, h, and can be given as:

$$r(h) = h * \tan(\theta)$$

The plume will have a circular cross-sectional area.

Therefore,

$$A_{plume} = \pi r^2 = \pi * h^2 * \tan^2(\theta)$$

The equations can be combined to give a relation between h and $\dot{m}$.

$$\frac{\dot{m} * U_{exp}}{A_{plume}} = P_{tube}$$

$$\frac{\dot{m} * U_{exp}}{\pi * h^2 * \tan^2(\theta)} = P_{tube}$$

Rearranging the above equation gives:

$$h^2 = \frac{\dot{m} * U_{exp}}{\pi * P_{tube} * \tan^2(\theta)}$$

$$h = \sqrt{\frac{\dot{m} * U_{exp}}{\pi * P_{tube} * \tan^2(\theta)}}$$

Substituting h in equation,

$$r(h) = h * \tan(\theta)$$

$$r = \sqrt{\frac{\dot{m} * U_{exp} * \tan^2(\theta)}{\pi * P_{tube}}}$$

Using the derived equation to calculate the plume size, a desired resolution of the detection sensor can be determined. Here, a leak of radius 0.25 mm is assumed in the vacuum tube.

$$\dot{m} = \rho * A * U$$

$$A = \pi r^2$$

$$\dot{m} = 0.76 * \left(\pi * 0.00025^2\right) * 313.29 = \mathbf{4.68 * 10^{-5}}\ \boldsymbol{kg/s}$$

$$h = \sqrt{\frac{\dot{m} * U_{exp}}{\pi * P_{tube} * \tan^2(\theta)}}$$

$$h = \sqrt{\frac{4.68 * 10^{-5} * 639.73}{\pi * 100 * 4.26^2}} = \mathbf{2.29 * 10^{-3}}\ \boldsymbol{m}$$

$$r(h) = h * \tan(\theta)$$

$$r(h) = 2.29 * 10^{-3} * 4.26 = \mathbf{9.76 * 10^{-3}}\boldsymbol{m}$$

The detection window, t, for such a leak is the time pod would take to cross the full width of the plume, W_{plume}. The full width of the plume is $2r$, calculated as $\mathbf{19.52 * 10^{-3}}\ \boldsymbol{m}$. The pod speed U_{pod}, is 200 km/h or 55.56 m/s. Therefore, the detection window is calculated to be:

$$t = \frac{W_{plume}}{U_{pod}}$$

$$t = \frac{19.52 * 10^{-3}}{55.56} = \mathbf{3.51 * 10^{-4}}\boldsymbol{s}$$

Applying a reliability factor of 30, the sampling frequency, f, is calculated as:

$$f = \frac{1}{3.51 * 10^{-4}} * 30 = \mathbf{85470\ Hz}$$

A leak radius vs resolution graph is plotted with varying leak size:

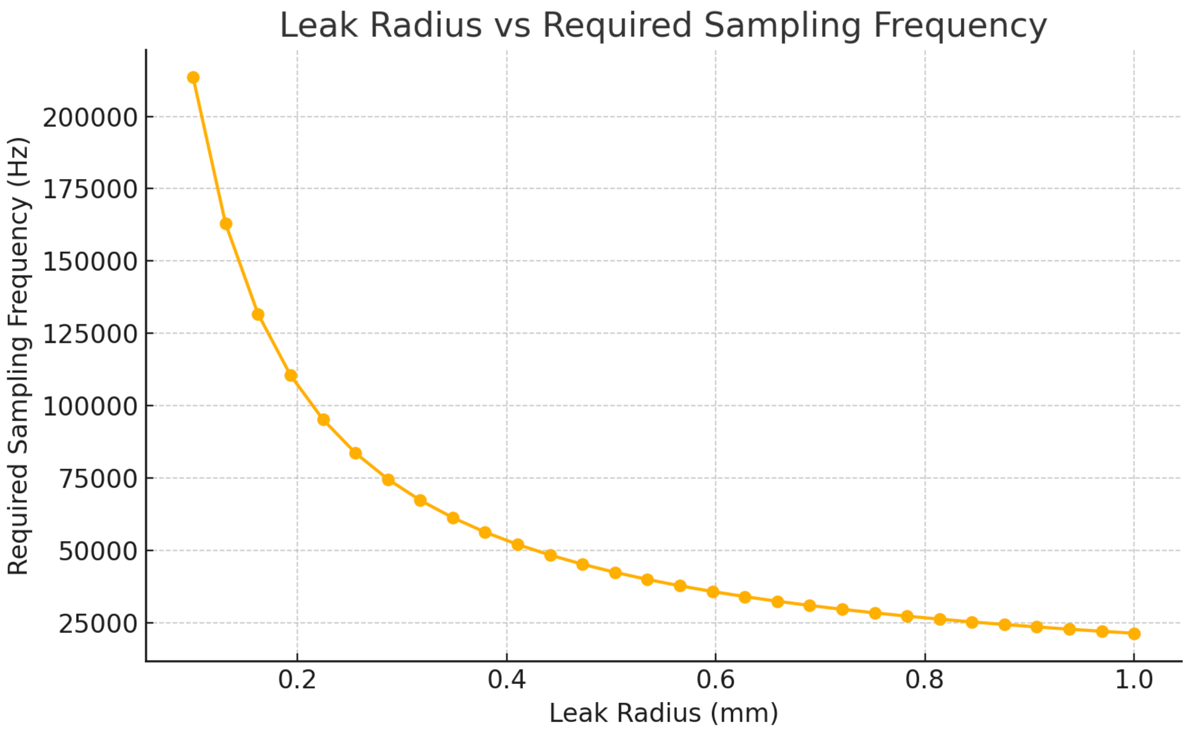

Figure 8: Sensor resolution for varying leak sizes

3.1.2 Propulsion and Levitation System

As previously discussed, high speeds nearing those of the Hyperloop passenger pods is not necessary or even desirable in a maintenance and repair pod. The design goals of the propulsion and levitation system for the pod therefore place focus on the reliability of the system and the ability to function in nonoptimal conditions. A failure in the power transmission to the pod or a compromise in the structural integrity of the tube are critical safety risks. These considerations necessitate a departure from conventional, single-mode propulsion to a hybrid propulsion system that combines the efficiency of magnetic levitation with the dependability of mechanical wheel propulsion.

The design process followed a structured approach:

1. Requirements definition: Establishing key performance indicators for the propulsion system based on the pod’s mission, including a target speed of 200 km/h, reliability, and compatibility with EHW track infrastructure.
2. Conceptual design: Developing concepts for the magnetic and mechanical propulsion system with a focus on leveraging the specified EHW track features.
3. Evaluating the concepts against a set of criteria including performance, complexity, mass, and reliability.
4. Digital modelling and simulation: Creating detailed digital models to serve as the basis for future performance validation through computer-aided simulation.
5. Proposed validation and verification: Outlining a plan for physical testing leading to a full-system demonstration.

3.2 Conceptual Design and Selection

3.2.1 Pod Design and Materials

Although the pod is designed for detection purpose, the aerodynamics of the pod remain a consideration as it has an operational speed of 200 km/h. The pods external shape must be streamlined to reduce drag and maintain stability, which ensures efficient travel and optimal sensor reading. The materials selected for the pod must balance factors such as, vacuum compatibility and low weight. A. material capable of meeting these criteria is a composite such as carbon fibre. Polymers ensure structural integrity without compromising performance at high speeds.

3.2.2 Pod Dimensions

To allow for the sensors to be integrated onto the pod the dimensions of the pod are as follows, the width and height required are 1.75m and the length required will be 2m. These dimensions allow for a compact pod that can travel within a hyperloop tube whilst containing the necessary sensing equipment, as well as ensuring adequate internal space for power supplies and memory components.

3.2.3 Sensor Integration onto pod

To allow for seamless integration and optimal performance of the sensors on board the pod a system architecture must be established. This entails mapping out each of the sensor's functional role, precise location, and how it interfaces with the pods central control system. Furthermore, detailed planning of power supply lines and data communication pathways is essential. Each of the sensors must be supported by an interference free connection to the onboard processing unit. To prevent electromagnetic interference the signal routes must be isolated where necessary, using techniques such as shielding or grounding. This is also paramount to consider around the sensitive magnetometers. The overall goal is to allow for data integrity and real time responsiveness. Although no design work has been complete, tools such as CAD software could be utilised for spatial layout. Aswell as this, Simulink could be used to validate integration and signal flow.

3.2.4 Sensor Dimensions

The first sensors to be integrated onto the pod are the two magnetometers to measure the magnetic field strength of the guideway. These sensors are located at the bottom corner of the pod facing the guideways of the track. The dimensions of these sensors are 25mm x 15mm x 30mm. The next sensor is the LIDAR sensor located near the nose of the pod. This sensor maps the curvature of the tube and has dimensions of 30 x 30 x 35mm.Also, there is the thermal imaging camera which measures the of high-power lines which are required to be looking up at a 45° angle. The dimensions are 250 x 100 x

150mm. Finally, also present on the pod will be 8 sensors each with a 200mm diameter. These sensors are placed inside the pod with a window allowing them to detect changes in air density within the tube, allowing the detection of leaks. These sensors are specifically called tuneable diode laser absorption spectroscopy (TDLAS).

3.2.5 Mounting the Sensors

The physical integration of the sensors ensures the sensors are securely mounted onto the pod in a position that optimises their performance. Also, the sensor must be compatible with the structure of the pod as well as allowing for reliable data collection under dynamic operating conditions, and ease of access for maintenance throughout the pod's lifetime. The magnetometers will be attached flush to the outer shell of the pod using brackets. In addition to this, due to the aforementioned high sensitivity of these sensors, they must be magnetically isolated from any other electronics. To allow for access for maintenance of these sensors small removable panels will be designed that can detach from the brackets. The LIDAR sensor will be mounted in a vibration isolated mount inside an open nose cone section. This sensor must be vibration isolated because, it relies on precise measurements to accurately map the curvature of the hyperloop tube. Any vibration within the tube and pod can introduce noise and distortion in the data due a slight shift in the sensors position during operation. There must be no obstruction to the field of view of the sensor, which would also affect overall sensor performance during operation. The use of LIDAR sensors can generate significant heat during continuous operation, therefore there is a need for ventilation for thermal management. The thermal imaging camera will be mounted inside a weatherproof casing with a thermal transparent window. The need for this is to protect the thermal imaging camera from the Hyperloop environment, particularly dust, moisture, and pressure fluctuations. The thermal imaging camera will be mounted using a fixed 45° bracket. The access to maintenance will be a similar design to the magnetometers using a small removable panel. Finally, the TDLAS sensors will be mounted in a symmetrical layout along the pod's length and circumference. There will be a total of four sensors on each side. There will also be an integration of optical grade windows in the pod body aligned with each sensor. Although no physical modelling and testing has been conducted for this stage, in future the development of this stage will be conducted using CAD tools. Followed by the use of ANSYS to investigate structural performance, vibration isolation, and airflow for sensor cooling.

3.3 Simulation and Modelling Tools

3.3.1 Propulsion and Levitation System

As this is a conceptual study, the methodology involved the selection and use of software tools for digital validation of the design:

- Computer-Aided Design (CAD): Large parts of the undercarriage were modelled using Creo, and can serve as inputs for further simulations.
- Electromagnetic simulation (future work): the performance of the magnetic levitation and propulsion system can be validated using software such as Abaqus.
- Finite Element Analysis (FEA) (future work): The structural integrity of the undercarriage will be analysed using Abaqus.

3.4 Test Setup and Procedures

3.4.1 Propulsion and Levitation System

To bridge the gap from concept to reality, a phased testing methodology is proposed for future work:

1. Component-level bench testing: Individual components such as electromagnets and wheel drive motors will be tested on a static test rig in order to validate their performance against simulation data.
2. Subsystem integration testing: A small-scale prototype of the mechanical propulsion mechanism will be built and tested.
3. Full-system demonstration: A series of full-system tests will be conducted to verify the pod’s ability to achieve and maintain the target speed and ensure its reliability.

3.5 Limitations and Assumptions

3.5.1 Propulsion and Levitation System

This study is conceptual, and all performance metrics are currently theoretical. The design has not yet been validated through physical prototyping or extensive simulation. In addition, the aerodynamic forces acting on the pod within the low-pressure tube environment have not currently been considered in the design of the propulsion and levitation system as they are assumed to be relatively low.

3.6 Electronics & Software Design Approach

The initial design methodology for this sub-system focused on a fundamental operational question: how would the pod communicate with the control centre from within a sealed, signal-blocking tube? Two primary models were considered. The first was a “store-and-forward" approach, where the pod would gather data during its mission and only transmit it for analysis upon its return. This model was rejected due to significant operational inefficiencies and critical safety concerns, as it would prevent real-time response to system failures or unexpected events.

Consequently, the team established that a live, real-time telemetry system was a mandatory requirement. Having made this foundational decision, the subsequent methodology was to architect a communication framework capable of supporting this. This involved a comparative analysis of wireless technologies to ensure reliability, and the development of a tiered data management strategy to prioritise time-sensitive commands, ensuring the system is both robust and responsive enough for its mission-critical tasks.

4. Results

4.1 Design Outputs

4.1.1 Propulsion and Levitation System

The primary design consideration for the repair pod is operational reliability under all conditions, including power failure or track damage. Therefore, a hybrid propulsion strategy was adopted. The foundation of this strategy is a mechanical wheel-drive system, which ensures mobility when the primary magnetic system is unavailable. The primary purpose of the mechanical wheel-drive system is to provide low-speed, precise manoeuvring in the tube when needed; allow for fail-safe operation in the event of a power outage to the main track or traversing damaged sections of the maglev guideway; and to potentially enable a towing capability for stranded pods.

The design for this system was based on a train undercarriage and wheels, and consists of a driven axle, the wheels themselves, frames, and suspension springs (Fig. 9-10). The wheels were designed with a slight chamfer which produces lateral guidance forces. The wheels are driven by the axle through a keyed shaft and are held in place on one end by a welded rim on the axle, and on the other side by an axle hub with an internal roller bearing which connects to the frame.

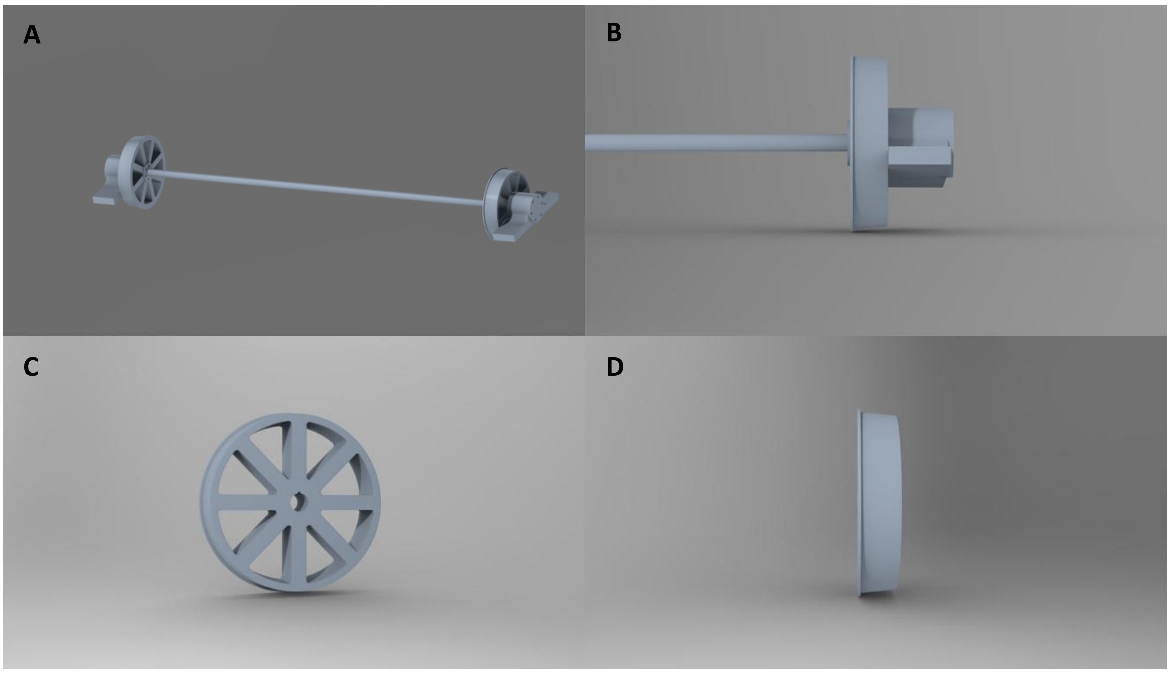

Figure 9: CAD models of the axle assembly and wheels: (a) the axle assembly; (b) the wheel assembly; (c) the wheel itself; (d) side view of the wheel model.

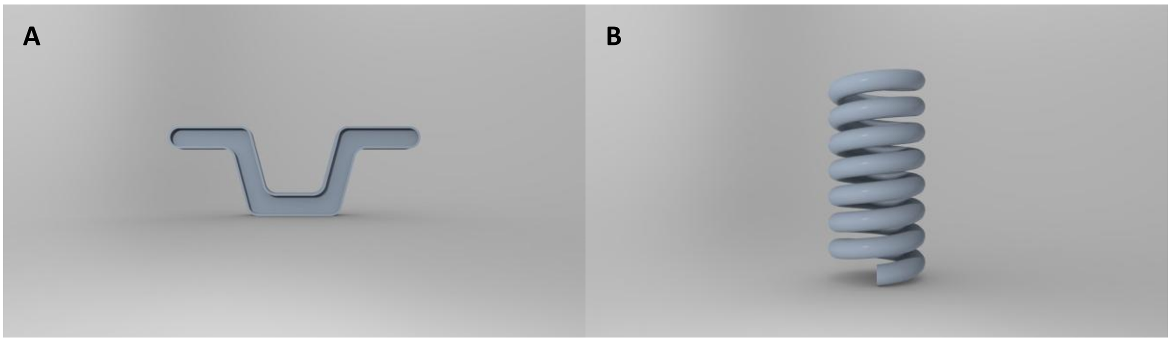

Figure 10: CAD models of undercarriage components: (a) side frame connecting adjacent axle assemblies; (b) suspension spring which connects to the frame and chassis.

The entire wheel and axle assembly would be mounted to the chassis through actuators. This would make the assembly retractable, which is essential for the functionality of the primary magnetic propulsion system. At high speeds or when the mechanical wheel-drive system is not needed, the assembly would be retracted upwards, clear of the track. At low speeds or during an emergency, the assembly would be deployed and contact the track. This is a well-developed technology which is commonly utilised in maglev trains employing EDS levitation.

The primary propulsion system is a Linear Reluctance Motor (LRM), specifically designed to interact with the EHW infrastructure. The system consists of an array of onboard electromagnets that are sequentially energised. This creates a travelling magnetic field that attracts the passive, laminated steel blocks of the propulsion track, generating a propulsive force.

4.1.3 Electronics and software architecture

To meet the mandatory requirements for a live telemetry system, the following multi-layered communication architecture was designed:

To overcome the signal-blocking nature of the hyperloop tube, a private, high-performance data "highway" must be built. The core principle of this design is redundancy, ensuring mission continuity by never relying on a single point of failure.

The Physical Link

Main Highway: A Private 5G Network: Small 5G mm Wave antennas installed every few hundred meters along the tube's interior create a continuous bubble of high-speed connectivity. 5G is chosen over alternatives like Wi-Fi or 4G for three key reasons: its inherent design for high-speed mobility and seamless handover; its native support for ultra-low latency; and its network slicing capability. This allows the creation of separate virtual networks, such as a high-priority, guaranteed-speed "slice" for critical control commands that is never slowed down by other data traffic, a feature not present in alternatives.

Backup Highway: Li-Fi (Light Fidelity): A parallel system of specialised LED lights installed within the tube provides a redundant data link. By modulating light at imperceptible speeds, data is transmitted to a receiver on the pod. Li-Fi is the ideal backup because it is a very different technology in that it uses light, not radio waves, making it completely immune to the electromagnetic interference (EMI) that could be generated by the pod's own tools (e.g. welders) and disrupt the 5G signal. Its physically contained signal also provides enhanced security from outside attackers.

Data Management ("Traffic Rules")

Different tasks require different data handling, managed by specific network protocols.

- **Priority 1: Instant Commands and Controls (Modified UDP):** For real-time control of the pod's movement and robotic tools, a protocol based on UDP (User Datagram Protocol) is used. It is chosen for its raw speed, modified with a lightweight confirmation layer to ensure the delivery of critical commands without the overhead of standard TCP.
- **Priority 2: Live Feeds & Active Sensors (WebRTC):** For streaming multiple HD video feeds, audio, and live diagnostic data (e.g., from a thermal scanner), WebRTC (Web Real-Time Communication) is employed. This is the proven standard for real-time, multi-stream media, designed to provide a smooth, low-lag experience for the operator.
- **Priority 3: Background Monitoring and Logs (TCP):** For all non-urgent health data and system logs, the standard TCP (Transmission Control Protocol) is used. Its focus on 100% data integrity over speed is perfect for ensuring that logs for post-mission analysis are complete and error-free.

Core Operational Challenges

The proposed architecture is designed to overcome three fundamental engineering hurdles.

- **Latency (The 20ms Barrier):** For the operator to have effective, natural control over the remote tools, the round-trip delay must be below the threshold of human perception, which research in telerobotics and VR has established at approximately 20 milliseconds. The selection of a 5G uRLLC (Ultra-Reliable Low-Latency Communication) system is a direct solution to meeting this strict requirement.
- **Bandwidth Demand:** The pod acts as a data firehose, simultaneously streaming multiple 4K video feeds and complex sensor data. The high capacity of 5G mm Wave is essential to handle this massive, sustained data rate without cutting back on quality.
- **Cybersecurity Threat:** A remote-controlled pod with powerful tools is a high-value target. The system must be protected against hijacking. A "Zero Trust" security model is implemented, meaning no command is trusted by default. Every instruction sent to the pod must be cryptographically signed and authenticated, ensuring that even if an attacker breaches the network, they cannot issue unauthorized commands.

The Digital Twin: An Intelligent Operations Platform

The Digital Twin is the "brain" that leverages the data provided by the communication "nervous system." This section details how the Digital Twin leverages high-fidelity data from the communication network to overcome the inherent challenges of remote operation and unlock transformative capabilities that define the system's value.

The Challenge of Remote Operation: The Information Gap

A human operator controlling the pod from a remote centre faces significant perceptual limitations that would not exist if they were physically present. A simple video feed, no matter how high the quality, cannot bridge this "information gap." The operator has a lack of peripheral vision, a lack of true depth perception, and no access to the physical instincts that are crucial for complex manual tasks. These limitations present a significant risk of error and inefficiency when performing high-stakes work.

The Digital Twin as a Solution

To overcome these challenges, the system architecture incorporates a comprehensive Digital Twin. This is a live, real-time virtual replica of the entire hyperloop ecosystem, built from a "system of systems" approach. It includes detailed models of the maintenance pod, every section of the tube infrastructure, and the operational physics of the environment. Its primary purpose is to process the vast amounts of data delivered by the communication architecture and translate it into actionable, intuitive intelligence.

Key Capabilities in a Repair Mission

The Digital Twin provides three core benefits that directly enhance the capabilities of the maintenance pod, moving it from a simple remote-controlled tool to a precision instrument.

1. Virtual Mission Rehearsal: Inspired by flight and surgical simulators, the digital twin allows for the complete rehearsal of a repair mission. After the pod performs an initial non-contact diagnostic run to scan the fault with 3D lasers, the data is used to create a high-fidelity virtual model of the damage. The operator can then practice the entire repair in this safe, virtual environment, de-risking the live mission and optimising their strategy.

2. Live Augmented Reality (AR) Overlays: The twin provides the operator with real-time AR "superpowers," projecting data onto their live video feed. This concept is inspired by proven industrial systems, such as Microsoft's HoloLens in aerospace maintenance. Key features include:

- **"X-Ray Vision":** Outlines of hidden components like power conduits behind solid panels.
- **Live Data Display:** Real-time sensor readings (e.g., temperature, voltage) floating next to the relevant component.
- **Procedural Guidance:** Highlighting the correct sequence of actions or displaying virtual alignment guides for precise installations.

3. Predictive Maintenance: The twin's most significant long-term value lies in its ability to predict component failures. By establishing a "Golden Record" of the pod's performance when brand new and constantly comparing live data to this baseline, it can perform long-term trend analysis. It can detect that a motor's energy consumption has slowly increased by a fraction of a percent over dozens of missions and forecast a future failure point, allowing maintenance to be scheduled proactively.

Sub-system Conclusion

The successful operation of a hyperloop maintenance pod is fundamentally a communication and software challenge. The proposed architecture, a redundant 5G and Li-Fi network managing prioritised data streams, provides the necessary foundation of reliability, speed, and security for this sub-system. It is the recommendation of this team that this design be adopted as the standard for remote operations. This robust connection enables the use of a comprehensive Digital Twin, which closes the information gap for remote operators through virtual rehearsals, augmented reality, and predictive analytics. For the maintenance pod, the communication link is not merely an accessory; it is the core enabling platform that makes its complex and critical mission possible.

4.2 Validation of Results

The validation of results for this project aligns with its status as a conceptual design study. As such, comprehensive validation through extensive simulation or physical prototyping has not yet been performed, and all performance metrics are currently theoretical.

The primary validation at this stage has been through digital means. Large portions of the undercarriage have been modelled using Computer-Aided Design (CAD), and these models will serve as the basis for future performance validation through simulations like Finite Element Analysis (FEA) and electromagnetic simulation. The overall feasibility and safety of the pod concept were validated at a high level through the use of scenario-based simulations and risk assessment methodologies, such as the Risk Priority Number (RPN) analysis. A detailed framework for future physical validation has been proposed, outlining a phased testing plan that includes component-level testing, subsystem integration, and a full-system demonstration to bridge the gap from concept to a verified physical system.

5. Discussion

5.1 Interpretation of Results

The design outputs for the repair pod are directly aligned with the project's primary aim of ensuring operational reliability in all conditions, including power failures or track damage. The adoption of a hybrid propulsion strategy, combining a mechanical wheel-drive system with a primary Linear Reluctance Motor (LRM), is a direct response to this requirement. The mechanical system provides essential low-speed manoeuvrability, fail-safe operation in the event of a power outage or damaged maglev guideway, and the potential to tow stranded pods. The retractable nature of the wheel and axle assembly is crucial for the effective operation of the primary magnetic propulsion system at higher speeds. This dual-mode functionality ensures that the pod can navigate the Hyperloop tube under a wide range of operational scenarios, fulfilling a key project objective.

The choice of an LRM for the primary propulsion system is justified by its reliability and the cost-effectiveness of its passive track, which aligns with the project's emphasis on a robust and simple system. The LRM design, which interacts with the EHW infrastructure's passive steel blocks, demonstrates a practical approach to system integration. The sequential energising of onboard electromagnets to create a travelling magnetic field is a well-established principle for generating propulsive force, providing confidence in the conceptual design's viability.

5.2 Comparison with Established Literature

The conceptual design of the Liverpool Hyperloop repair pod addresses a significant gap identified in the existing literature, which has predominantly focused on passenger transport and tube construction with limited consideration for long-term maintenance. While many proposed Hyperloop systems are based on mature magnetic levitation and propulsion technologies like EMS and EDS, this project deviates by prioritising reliability for a maintenance pod over the high speeds desired for passenger pods.

The project's literature review identified structural failure and power transmission failure as critical safety risks. The proposed hybrid propulsion system directly confronts these challenges by providing a redundant mechanical mobility option, ensuring the pod can function even if the primary maglev system or its power supply is compromised. This is a notable departure from the single-mode propulsion systems discussed in much of the literature. Furthermore, the selection of a Linear Reluctance Motor (LRM) with its passive, robust track is a deliberate choice for reliability, contrasting with more complex systems like LSMs which require intricate control systems. The inclusion of advanced sensor technologies for detecting issues such as tube ovalness, deformation, and thermal anomalies in cables also represents a practical application of diagnostic principles to address the failure modes identified in the literature, such as ductile fracture and buckling.

5.3 Design Challenges and Limitations

A primary challenge encountered during the conceptual design phase was the inherent trade-off between the speed of inspection and the quality of sensor data. It was determined that the repair pod could not travel at the same high speeds as passenger pods because this would compromise the accuracy of sensor measurements and the clarity of visual data capture. Consequently, a reduced operational speed of 200 km/h was selected as a necessary compromise to ensure reliable data collection from sensors.

Given the significant differences in the thermodynamic properties between the under-expanded jet and the ambient air within the tunnel, both thermal and density-based detection methods offer viable approaches for identifying the presence of a leak. However, the use of a density sensor may present certain advantages in terms of reliability and effectiveness.

A thermal imaging camera operates by detecting variations in surface temperature. In the context of a high-angle expansion, such as the 77-degree plume considered here, the extent to which the jet interacts with the tunnel wall will depend on the radius of curvature of the tunnel. Furthermore, the material properties of the wall, including thermal conductivity, specific heat capacity, and surface emissivity, will influence the heat transfer characteristics. These factors, in turn, affect the size and persistence of the temperature gradient zone, and may cause rapid attenuation of the thermal signature, particularly in the case of small or transient leaks. As a result, thermal imaging may not consistently produce a distinguishable signal under varying material and flow conditions.

In contrast, a density sensor provides a direct measurement of gas-phase properties and is not influenced by the thermal response or composition of the surrounding wall. The sharp contrast in density between the high-speed under-expanded air and the low-pressure ambient environment offers a clear signal for detection. Moreover, this method is particularly well suited to non-contact sensing from a diagnostic pod in motion, as it captures the internal flow characteristics rather than relying on wall interaction effects.

Therefore, while both techniques have merit, the application of a high-speed density sensor is likely to yield more consistent and interpretable results for the detection of micro-leaks within a vacuum tunnel. Its independence from wall material properties and its sensitivity to localised flow disturbances make it a preferred choice for this specific diagnostic scenario.

A significant limitation of this project is its conceptual nature. All performance metrics are currently theoretical and have not been validated through physical prototyping or extensive simulation. The design of the propulsion and levitation system, for instance, has not yet accounted for the aerodynamic forces within the low-pressure tube, which are assumed to be relatively low. The report also intentionally excludes detailed manufacturing processes, as its purpose is to establish a foundational framework for future development rather than a finalised engineering solution. Future work will be required to bridge the gap from concept to a physically validated system.

5.4 Implications for Future Development

The foundational study presented in this report has the potential to significantly influence the future development of Hyperloop technology by shifting focus towards the critical, yet often overlooked, area of maintenance and system longevity. By establishing a conceptual framework for a remotely operated repair pod, this work provides a roadmap for ensuring the safety, reliability, and economic viability of future Hyperloop systems. The proposed hybrid propulsion system, advanced sensor suite, and remote operation capabilities offer a new perspective for infrastructure maintenance in the unique Hyperloop environment, moving away from the inadequate conventional railway repair strategies.

The successful development and integration of such a repair pod would make Hyperloop transportation systems more resilient to operational disruptions, thereby improving their overall safety and efficiency. This research encourages further technical investigation and system integration in subsequent project phases, laying the groundwork for future prototyping and development. Ultimately, by addressing the practical challenges of maintenance and repair, this project contributes to building confidence in Hyperloop technology and advancing its readiness for widespread deployment.

6. Conclusion & Future Works

6.1 Recommendations for Future Development

To advance this conceptual design towards a functional prototype, a phased approach focusing on simulation, physical testing, and integration is recommended. The following steps will be critical in validating and refining the proposed repair pod system:

- **Electromagnetic and Structural Simulation:** Future work should prioritise the use of simulation software such as Abaqus to validate the performance of the magnetic levitation and propulsion system and to conduct Finite Element Analysis (FEA) on the structural integrity of the undercarriage. These simulations will provide essential data to refine the digital models created in Creo and ensure the designs can withstand the operational stresses of the Hyperloop environment.
- **Component-Level Prototyping and Testing:** It is recommended to proceed with component-level bench testing of individual elements, such as the electromagnets for the LRM and the motors for the mechanical wheel-drive system. These tests, conducted on a static rig, will serve to validate their performance against the simulation data and confirm their suitability for the application.
- **Subsystem Integration and Testing:** Following successful component tests, a small-scale prototype of the mechanical propulsion mechanism should be constructed and tested to evaluate its real-world performance. This will allow for the assessment of the deployment and retraction system and the interaction of the wheels with a track surface.
- **Full-System Demonstration:** The ultimate goal of future work should be a series of full-system tests using an integrated prototype. These demonstrations are necessary to verify the pod's ability to achieve its target speed, to test the seamless switching between propulsion modes,

and to confirm the overall reliability and safety of the integrated system. This will provide the definitive validation of the conceptual design and lay the groundwork for a pre-production model.

6.2 Final Remarks

For the Liverpool Hyperloop Team, this research showcases the opportunity to build physically on this project. As the team look for sponsorship opportunities and further support growing at the University of Liverpool, we hope to achieve the mentioned future developments. We have noticed significant external interest from global companies in the team itself, which presents opportunities to design, build and test this project for the upcoming years. Hoping to utilise software such as electromagnetic field solvers and specific Ansys packages for our proposed propulsion system, build prototypes of rigs for the mechanical wheel systems and purchase the sensors for subsystems integration are a few of the many opportunities available as the project drives forward, following the feedback from European Hyperloop Week and the University of Liverpool support.

With only being founded this year, a lot of time has been devoted to organising and recruitment of the team, working on social media and our website and setting up academic support and funding. This has meant that not as much time has been devoted to the project as we would have liked, however, with this all being set up already, we look forward to the new academic year to build on this project and the opportunity on feedback given by this competition. Which will hopefully provide us with a critique to improve this design and have opportunities to take a step beyond and take part in the full-scale submissions and testing.

We would like to thank the European Hyperloop Week for providing the opportunity to take part in this competition and hope this starts the beginning of more related activities in the future.

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