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Case Study of an Integrated Design and Technical Concept for a Scalable Hyperloop System

Domenik Radeck , Florian Janke , Federico Gatta , João Nicolau , Gabriele Semino , Tim Hofmann , Nils König , Oliver Kleikemper , Felix He-Mao Hsu, Sebastian Rink , Felix Achenbach  and Agnes Jocher 

TUM School of Engineering and Design, Technical University of Munich, 85521 Ottobrunn, Germany; florian.janke@tum.de (F.J.); federico.gatta@tum.de (F.G.); joao.mp.nicolau@tum.de (J.N.); gabriele.semino@tum.de (G.S.); tim.hofmann@tum.de (T.H.); nils.koenig@tum.de (N.K.); oliver.kleikemper@tum.de (O.K.); felix.hsu@tum.de (F.H.-M.H.); sebastian.rink@tum.de (S.R.); felix.achenbach@tum.de (F.A.); agnes.jocher@tum.de (A.J.)

* Correspondence: domenik.radeck@tum.de

Abstract: This paper presents the design process and resulting technical concept for an integrated hyperloop system, aimed at realizing efficient high-speed ground transportation. This study integrates various functions into a coherent and technically feasible solution, with key design decisions that optimize performance and cost-efficiency. An iterative design process with domain-specific experts, regular reviews, and a dataset with a single source of truth were employed to ensure continuous and collective progress. The proposed hyperloop system features a maximum speed of $600 \frac{\text{km}}{\text{h}}$ and a capacity of 21 passengers per pod (vehicle). It employs air docks for efficient boarding, electromagnetic suspension (EMS) combined with electrodynamic suspension (EDS) for high-speed lane switching, and short stator motor technology for propulsion. Cooling is managed through water evaporation at an operating pressure of 10 mbar, while a 300 kW inductive power supply (IPS) provides onboard power. The design includes a safety system that avoids emergency exits along the track and utilizes separated safety-critical and high-bandwidth communication. With prefabricated concrete parts used for the tube, construction costs can be reduced and scalability improved. A dimensioned cross-sectional drawing, as well as a preliminary pod mass budget and station layout, are provided, highlighting critical technical systems and their interactions. Calculations of energy consumption per passenger kilometer, accounting for all functions, demonstrate a distinct advantage over existing modes of transportation, achieving greater efficiency even at high speeds and with smaller vehicle sizes. This work demonstrates the potential of a well-integrated hyperloop system to significantly enhance transportation efficiency and sustainability, positioning it as a promising extension to existing modes of travel. The findings offer a solid framework for future hyperloop development, encouraging further research, standardization efforts, and public dissemination for continued advancements.

Keywords: design decisions; technical concept; hyperloop; maglev; magnetic levitation; magnetic propulsion; system overview; high-speed transportation



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1. Introduction

High-speed ground transportation has the potential to replace most of the flights within Europe. Being fully electric, the system could significantly reduce the negative environmental impact caused by air travel, contributing to the fight against climate change while allowing for similar travel times between metropolitan areas. In addition to this, a hyperloop offers several other benefits such as fast city-to-city commutes, silent operation, and reliable low-maintenance service with reduced external influences thanks to the controlled environment of the tube and flexible on-demand operation.

While there is substantial research on the various technical challenges of the hyperloop system, such as aerodynamics [1,2], levitation [3], or communication [4], as well as on

system parameter optimization [5,6], relatively few studies provide a comprehensive technical overview [7–9]. This gap highlights the need for detailed studies that design and propose an overall functional technical system.

In addition to this scientific literature, the hyperloop industry has also contributed by publishing detailed reports on their technical concepts. The company Hardt Hyperloop (Rotterdam, Netherlands), for instance, proposes a system with electromagnetically levitating vehicles suspended from the top of the tube [10]. This design aims to optimize for a high-speed and high-frequency lane switch but comes with structural disadvantages that are further elaborated on in Section 4.3. On the other hand, EuroTube, a Swiss non-commercial foundation, presents a concept with electrodynamically suspended pods operating at the bottom of the tube [11], which promises to simplify the construction but increases the energy demand. Another valuable resource is the German Transrapid system, which, despite being discontinued and not having a low-pressure tube infrastructure, offers significant insights due to its comparable system complexity and numerous technical similarities with hyperloop, particularly in terms of track-bound transport systems and magnetic levitation. Extensive German literature on Transrapid [12] provides in-depth discussions on the challenges and solutions encountered in developing advanced transportation technologies. Building upon the findings from the Transrapid, the TSB is being developed in Germany for urban traffic, with a maximum speed of $150 \frac{\text{km}}{\text{h}}$ [13]. Despite its lower speed, the system serves as a role model for modern Maglev technology, particularly in terms of levitation and the packaging of subsystems. Within the framework of a comprehensive research program at Technical University Munich (TUM), a 24-m demonstrator was inaugurated in 2023, showcasing a functional and certified full-scale hyperloop test stand for low speeds [14]. The work provides insights into the design process and the engineering challenges faced during the development of this full-scale hyperloop test stand. The demonstrator serves as a critical step towards understanding the practical aspects of implementing a hyperloop system and helps in validating theoretical models through real-world prototyping.

Overall, while existing literature and industry reports provide important pieces of the puzzle, this study advances the state of the art by presenting a more integrated perspective, addressing the interplay between various functions and the overall feasibility of a full-scale, high-speed hyperloop system.

The objectives of this study are as follows:

- Show technical feasibility: Find a technical solution addressing the most common technical objections to the hyperloop concept.
- Demonstrate system cohesion: Illustrate that there is a set of parameters, requirements, and technical solutions that can function together harmoniously.
- Document design considerations: Provide a detailed documentation of the design considerations undertaken by the team.
- Support standardization process: Propose a technical concept to provide a foundation for standardization. The goal is to guide future detailed research within the hyperloop community and foster uniformity across different hyperloop projects.

2. Methodology

This research employs a systematic design method for the early conceptual design stage of the hyperloop system. While a hyperloop presents a unique opportunity to design a blank slate transportation system free from legacy issues, the lack of established boundary conditions poses significant methodological challenges. A structured yet iterative approach is essential to derive a meaningful set of solutions and parameters, which are highly interdependent.

Figure 1 provides an overview of the system functions addressed sequentially and iteratively, illustrating their technical interdependencies. In the center, some of the main system parameters are shown, highlighting their significant influence on the system functions.

On the other hand, understanding these functions in detail helps to define the parameters in a meaningful and coherent way.

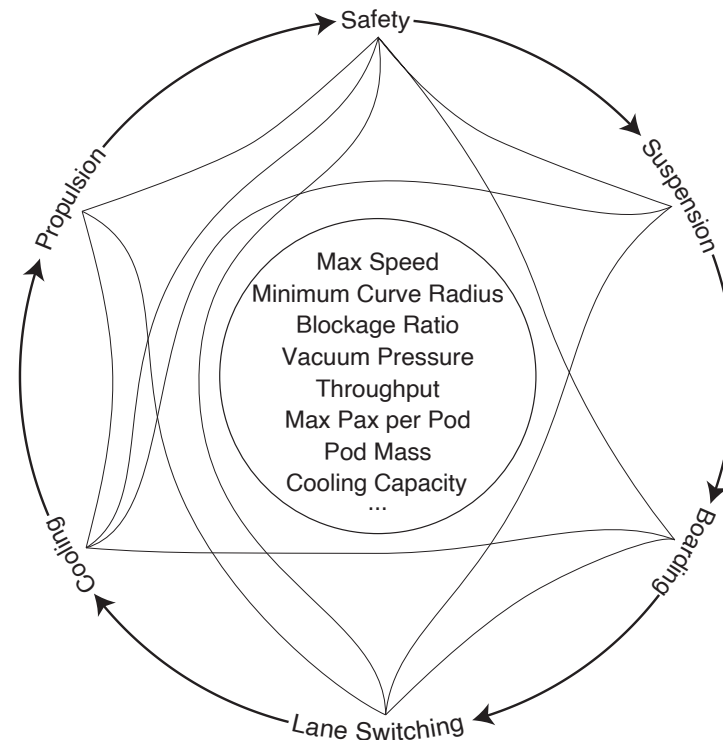


Figure 1. Illustration of essential hyperloop functions in the design loop (outer circle), their dependencies and important system parameters (center).

To accomplish this, experienced engineers involved in the TUM Hyperloop Demonstrator project worked together to develop a coherent hyperloop concept. Each team member brought expertise from different fields and delved deeply into their respective topics. The results were integrated into a single data table, allowing the team to immediately see any changes. This approach enabled the team to quickly identify and address problematic design points and tackle technical issues iteratively. The resulting impacts on other functions were evaluated and continuously used to refine the design decisions. As indicated in the outer circle of Figure 1, this process occurred sequentially, function-by-function, to achieve a coherent set of feasible solutions and parameters. Regular discussions and reviews with industry experts ensured continuous progress and alignment towards feasibility.

In systems engineering, this phase of work is classified as the concept definition phase of the system life cycle, as depicted in Figure 2. It follows an in-depth concept exploration resulting in different candidate system concepts and a first set of system performance requirements. As indicated, the output of the work is a set of system functional specifications and the presentation of a defined system concept to prepare for an advanced development in the next stage. According to Kossiakoff et al. [15], the following four activities are of major importance in the concept definition phase: requirement analysis, functional definition, physical definition, and design validation. This study adheres to this framework, initially focusing on the functional definition. Subsequently, the physical definition presents how these functions are allocated to subsystems with their components and how those components are packaged into the proposed design. Requirement analysis and design validation are iterative processes that recur while alternative concepts are evaluated. Both the requirement analysis and the design validation were ensured by the central data table. Therefore, system validity could be quantified. The table was also used to review and refine the system's requirements.

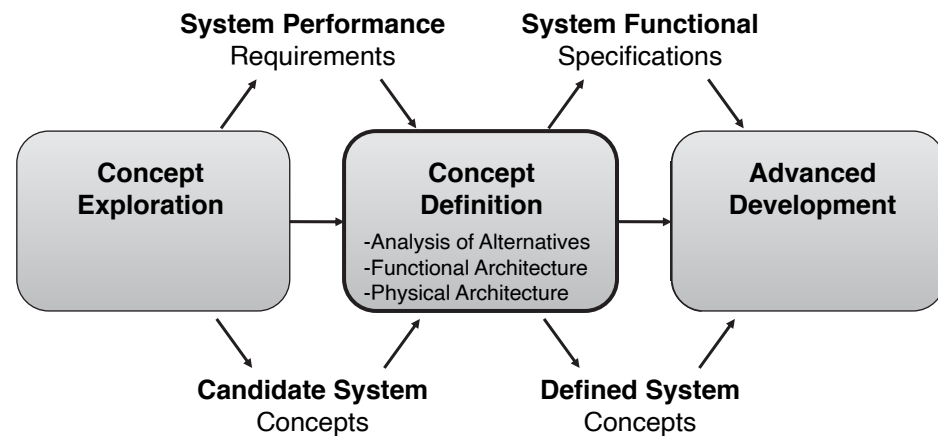


Figure 2. Illustration of the concept definition phase in the systems engineering life cycle adopted from [15].

The accompanying data table summarizing all the values presented in this work and their respective calculations is available online <https://concept.tumhyperloop.com> (accessed on 7 November 2024). In the tables, the gray cells represent the calculated values, while cells with a white background show the input parameters. Peak always refers to the peak hour, or in this case, the maximum throughput the system can achieve.

The coordinate system used in this analysis is defined as follows: x is the direction of travel, y points to the right side, and z points upwards.

The following section outlines the targeted concept of operation, followed by a section on the detailed description of the main functions of the hyperloop system, including boarding, suspension, lane switching, propulsion, power, cooling, and safety. Subsequently, the key elements of the system—namely the tube, the pod, and the stations—are presented.

3. Concept of Operation

The hyperloop, instead of upgrading existing transportation systems, presents an unparalleled opportunity to make radical improvements without legacy issues, fully exploiting today's technologies. This approach, however, poses significant engineering challenges, as it involves establishing boundary conditions and deriving most requirements from scratch, often with multiple conflicting technical goals. To address this unique blank sheet problem, the following work establishes fundamental requirements through thorough reasoning of each value.

Table 1 outlines the governing parameters for the design of the system in later chapters. In the following, the chosen parameters are described in detail.

Determining the maximum speed requirement is crucial, as it impacts most functions of the hyperloop system. In Europe, two key factors influence the maximum speed requirement for ground-based transportation systems. Firstly, existing transport corridors often permit a minimum curve radius of at least 7000 m [16]. With appropriate banking, maintaining speeds between $500 \frac{\text{km}}{\text{h}}$ and $600 \frac{\text{km}}{\text{h}}$ while adhering to this curve radius is feasible. For instance, Table 1 illustrates that curve radii under 5 km are achievable without exceeding acceleration limits at a nominal speed of $530 \frac{\text{km}}{\text{h}}$. Secondly, the speed requirements are influenced by relatively short inner continental distances. Figure 3 displays travel distances and corresponding times for various modes of transportation, with corresponding assumptions detailed in Table 2. These parameters were selected based on example routes within Europe. Since ground-based transportation requires traveling longer distances than air travel, a route length factor was introduced. Additional time overheads such as traveling to the station and airport security checks or taxiing are considered. Under these assumptions, the hyperloop emerges as the fastest mode of transport for distances up to 2542 km, beyond which air travel becomes more efficient. This crossing point is also marked as a black dot in Figure 3. For distances of up to approximately 1500 km,

hyperloop, with an average speed of $530 \frac{\text{km}}{\text{h}}$, it consistently outperforms air travel in terms of travel time. For shorter routes of up to 55 km, cars offer shorter travel times in most cases. Passenger transport through high-speed rail (HSR) could be fully substituted by the hyperloop, freeing important capacity for freight transport.

Table 1. General hyperloop system characteristics. Values with a grey background are calculated, while others are input values.

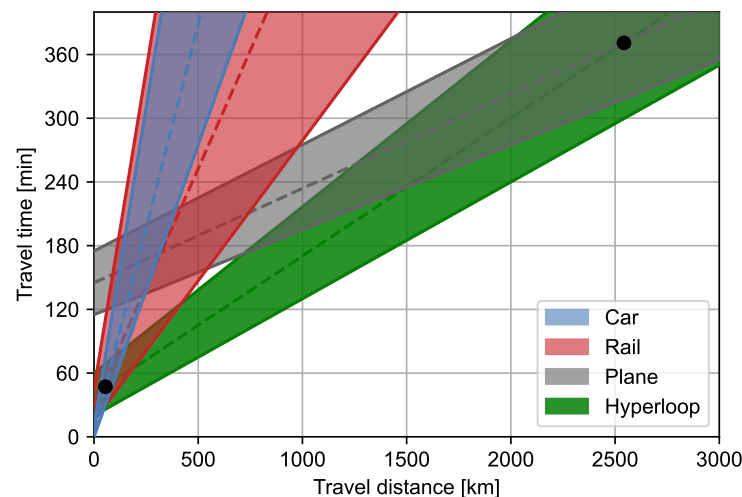
Description	Value
Max speed	$600 \frac{\text{km}}{\text{h}}$
Nom speed	$530 \frac{\text{km}}{\text{h}}$
Throughput main lane (peak, pax per direction)	$25,000 \frac{\text{pax}}{\text{h direction}}$
Pax per pod	$21 \frac{\text{pax}}{\text{pod}}$
Throughput main lane (peak, pods per minute)	$19.84 \frac{\text{pods}}{\text{min}}$
Pod density (max speed)	$1.98 \frac{\text{pods}}{\text{km}}$
Pod density (nom speed)	$2.25 \frac{\text{pods}}{\text{km}}$
Time between pods (peak)	3.02 s
Max propulsion power	3.00 MW
Max x -acceleration	$2 \frac{\text{m}}{\text{s}^2}$
Acceleration time (to max speed)	1.57 min
Acceleration time (to nom speed)	1.32 min
Acceleration distance (to max speed)	8549 m
Acceleration distance (to nom speed)	6152 m
Max curve inclination angle	15°
Max z -acceleration	$2 \frac{\text{m}}{\text{s}^2}$
Max y -acceleration (unbalanced)	$2 \frac{\text{m}}{\text{s}^2}$
Min horizontal curvature radius	
at max speed without lateral acceleration	$10,568 \text{ m}$
Min horizontal curvature radius	
at nom speed without lateral acceleration	8246 m
Min horizontal curvature radius	
at max speed with lateral acceleration	5911 m
Min horizontal curvature radius	
at nom speed with lateral acceleration	4612 m

Existing ground-based high-speed systems like maglev trains can achieve maximum (max) speeds of $600 \frac{\text{km}}{\text{h}}$ or higher but typically reach low average speeds due to frequent stops, making them time efficient only for direct point-to-point connections. Maglev systems offering frequent direct connections with smaller trains but without traveling in a vacuum environment come with a high energy demand per seat. This is where hyperloop technology provides a unique opportunity for direct high-speed transportation at a lower energy demand per seat.

However, in a hyperloop system, higher speeds necessitate either larger tubes or result in reduced energy efficiency due to aerodynamic effects. To balance these requirements, the max speed was set to $600 \frac{\text{km}}{\text{h}}$, with a nominal (nom) speed of $530 \frac{\text{km}}{\text{h}}$. This decision is explicitly tailored for the European market. The focus is on adhering to existing corridors, achieving faster travel times than air travel within the continent, and prioritizing flexibility to connect smaller cities and sustainability through the use of smaller tubes over a maximum speed. In other markets that require direct point-to-point connections at maximum speed, the system can be adapted for higher speeds. However, this study concentrates on the requirements identified as best-suited for the European market.

Table 2. Assumed data to compare modes of transportation. Results are presented in Figure 3.

	Car	Rail	Hyperloop	Plane
Best-case overhead time [min]	0	15	20	115
Worst-case overhead time [min]	10	45	60	175
Best-case average speed [$\frac{\text{km}}{\text{h}}$]	120	250	600	750
Worst-case average speed [$\frac{\text{km}}{\text{h}}$]	60	60	460	600
Best-case route length factor	1.1	1.1	1.1	1.0
Worst-case route length factor	1.2	1.2	1.2	1.0

**Figure 3.** Travel time and distance comparison of different modes of transportation based on the data presented in Table 2. Between the black dots, the hyperloop offers the shortest average travel time compared to other modes of transport.

An acceleration requirement of $2 \frac{\text{m}}{\text{s}^2}$ was established. As shown in Table 1, this, combined with a 3 MW motor, enables acceleration to max speed in under 100 s and approximately 8.5 km.

The target throughput for the main lane was set at $25,000 \frac{\text{pax}}{\text{h direction}}$, compared to approximately $10,000 \frac{\text{pax}}{\text{h direction}}$ in high-speed rail. This corresponds to a pod every 3 s during rush hour or a convoy of 10 pods every 30 s.

4. Functional Definition

In the following, the main functions and technical challenges are addressed quantitatively to describe the technical functionality.

4.1. Boarding

To enter or exit the system, the vacuum environment must be overcome. Generally, there are two options to achieve this: either the pod is removed from the vacuum via an air lock, or the pod connects its interior to the outside using an air dock.

Air locks offer the advantage that low-speed parts of the track, as well as the stations, can be operated at atmospheric pressure, thereby reducing costs. On the other hand, air docks are expected to be faster in operation, more energy-efficient, and prevent cyclic loads on the cabin.

A common air lock with two gates and reasonably dimensioned pumps takes at least about 10 min to pump down to 10 mbar, which undermines much of the hyperloop use case. There are other theoretical proposals, such as using a column of water as an air lock that the pod has to pass through. Another option is to feature a combination of a blower that reaches a pressure of 300 mbar relatively fast, then releasing the rest of the air into the

tube. This design, however, involves substantial energy consumption. Additionally, all pods have to come to a full stop twice in the journey, prolonging travel time. Moreover, depending on the sound insulation, loud noises could reduce passenger comfort.

Conversely, air docks directly bridge the gap between the pod door and tube and allow for quick passenger boarding and deboarding operations. A pump system is required at the station to depressurize only the small volume between the pod door and station. Inflatable sealings are a favored way to implement this without lateral movement of the pod or the station interface. Due to space constraints in the cabin, the pod door should open outward while still providing airtight, safe, and reliable docking.

Given the advantages explained above, passenger boarding and deboarding using an air dock is selected. However, air locks will still be required at given locations—for example, at maintenance facilities—to move the pods into and out of the vacuum environment.

4.2. Suspension

The suspension of a vehicle traveling at $600 \frac{\text{km}}{\text{h}}$ is a challenging aspect of the hyperloop system. Technically, it is possible to suspend the pod with wheels similar to a train. However, at such high speeds, this approach is expected to be uneconomic due to the high maintenance costs and the difficulty of lubrication in a vacuum environment.

Electrodynamic suspension (EDS), which utilizes repelling forces between a conductor in the track and a permanent magnetic field in the vehicle, resulting in eddy currents, poses one viable concept. Nevertheless, the hyperloop community has converged on electromagnetic suspension (EMS), which uses attracting forces between ferromagnetic steel and a controlled electromagnet. This design is structurally more complex on the infrastructure side compared to the EDS design, but it reduces drag considerably and enables active damping. Unlike EDS, EMS enables levitation while the vehicle is stationary, which is an advantage for handling the pods and makes the incorporation of wheels unnecessary. More in-depth considerations on this topic can be found in a previous paper [14]. Table 3 summarizes the important parameters of the levitation and guidance (lev&guid) system.

To further reduce the drag induced by the levitation system, the arrangement plays a crucial role. In the Transrapid system, the levitation system is arranged in a heteropolar configuration due to its combination with propulsion, meaning that magnetic poles alternate in the driving direction. In contrast, the Transport System Bögl (TSB) arranges the levitation system in a homopolar configuration, maintaining a constant magnetic field over the entire length of the vehicle. This configuration reduces drag from the levitation system considerably and enables higher speeds, making it the preferred choice for a hyperloop system.

In the long term, increasing the air gap of the EMS would reduce the accuracy requirements for the track and simplify the mechanical suspension in the pod. One potential solution is the use of superconducting coils in combination with conventional copper coils, as researched in a test stand by Kalsi [17].

Additionally, the question of lateral suspension arises. Alongside similar considerations between EDS and EMS, there is the option to combine the EMS geometrically with a U-shaped counter plate in the track to achieve a passive guidance effect. However, due to the high speeds and resulting vibrations, this is not seen as sensible, and a separate active guidance system is therefore preferred.

Navigating dense urban environments and compact stations necessitates hyperloop pods that can handle tight curves, limited not by acceleration but by geometry — a common challenge for track-bound vehicles. Conventional trains use separate bogies with rotational freedom (Figure 4A) to navigate curves, but the hyperloop requires a “snake” system; a multi-bogie chain allowing for distribution of forces along the pod’s length.

A vertical spring dampening system compensates for curved elevation changes, limited by the maximum displacement differential along the snake. For horizontal curves, two design approaches exist. The first is a Transrapid-style layout, where each bogie retains

its stiff rectangular shape, joined to the carriage to enable translation in the y-direction and rotation around the z-axis (Figure 4B). This allows the snake to bend around curves, with increasing distance between outer levitation modules and decreasing distance between inner modules. The alternative approach, as utilized by several low-speed maglev systems [13,18,19], maintains a constant x-distance between individual modules on each side, particularly relevant for the motor concept described in Section 4.4. Here, each bogie can shift into a parallelogram shape to conform to the track (Figure 4C). This geometric transformation, however, increases the guidance airgap, which must be considered in the design.

Table 3. Suspension characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Number of bogie segments	7
Number of levitation modules	28
Number of guidance modules	14
Minimum curve radius	50 m
Nom power lev&guid	15 kW
Efficiency lev&guid	0.10
Nom heat from lev&guid	13.50 kW
Max power lev&guid	350 kW

The optimal number of bogies depends on the maximum allowable bogie length that stays within the airgap limits of the minimal curved track. Initial dimensioning shows that a parallelogram-shaped snake with seven bogies and a minimum curve radius of 50 m is reasonable in combination with the subsequent functions. Combining high-speed and minimal curve radii for low-speed urban maneuvering is expanding the state of the art significantly.

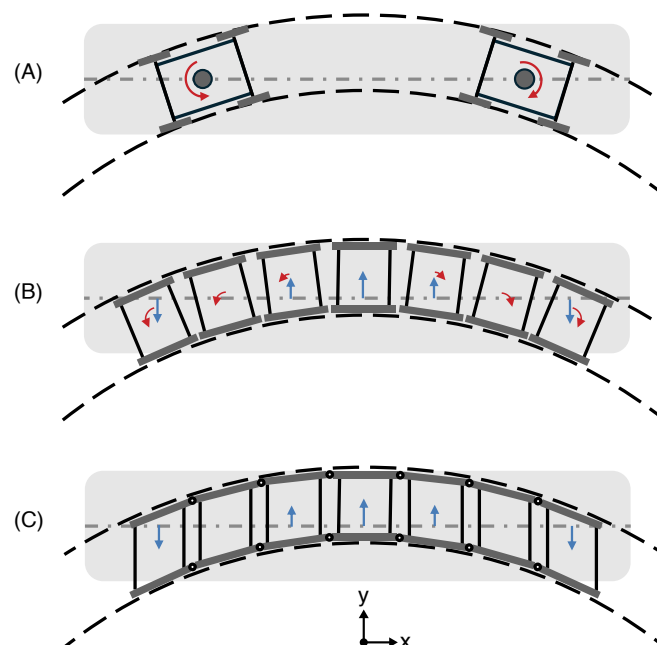


Figure 4. Conceptual sketch of bogie arrangements. Blue arrows indicate translational movement, while red arrows indicate rotation. (A) Conventional train layout, (B) Maglev layout via “bending” (rotation + shifting of each bogie), and (C) via “parallel shifting” (shifting + geometric deviation compensation). Adapted from [13].

4.3. Lane Switch

A fundamental chance for novel high-speed ground transportation, beyond achieving high speeds, is the ability to offer non-stop trips. High-speed trains often cannot provide this today because cities along the route in Europe demand connectivity, necessitating intermediate stops. This situation leads to the need for small, flexible pods to meet the varying demand. However, small vehicles are only feasible if:

- the aerodynamic drag and therefore the energy consumption is low, which is achievable due to the vacuum,
- the headway of vehicles is drastically reduced thanks to a modern traffic management system, potentially even to a distance where a pod cannot brake when the previous pod fails dramatically (covered in Section 4.7),
- there is a way to switch lanes at a high frequency and preferably full speed, rendering a mechanical lane switch on the infrastructure side impossible.

Although high-speed and high-frequency lane switching has not yet been tested in operation, several concepts are outlined in Figure 5.

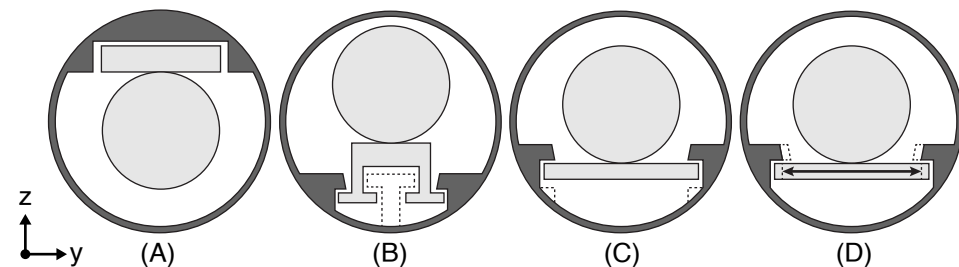


Figure 5. Conceptual sketches of different high-speed and high-frequency lane switching concepts for electromagnetic suspension. (A) Horizontal switching, hanging from the top. (B) Rail-like horizontal switching with a secondary electromagnetic system. (C) Vertical switching with a secondary electrodynamic system. (D) Vertical switching with a movable electromagnetic suspension.

- (A) Horizontal switching with the EMS mounted on top of the pod. This allows the nominal suspension to be used during lane switching. The downside is that the guidance system loses functionality during the switching process, and there are structural disadvantages: the force counteracting the weight of the payload has to be transmitted from the floor of the pod to the ceiling, then through the structure of the tube down to the foundation. This increases the structural costs of both the infrastructure and the pod.
- (B) Sinha [20] and Virgin Hyperloop [21] present a rail-like horizontal switching system without moving parts by equipping the levitation system with two magnetic iron circuits. Additionally, a concept is outlined to use only one electromagnetic coil for both the necessary magnetic circuits. A more detailed design created by the authors showed, however, that this option is geometrically impractical. Therefore, essentially two separate EMS systems would be required, both capable of carrying the entire load at full speed, leading to a significant mass increase.
- (C) Here, the nominal EMS system can be gradually turned off to land on a secondary EDS system; therefore, the pod can branch off by lowering itself vertically. The EMS and EDS tracks would then move apart in z -direction, completing the switch. After the switch, a new EMS track would appear, allowing the exiting pod to gradually turn on the EMS system and return to nominal levitation. Pods staying on the lane are not required to perform this transition, therefore keeping the number of transitions on a trip to a minimum. This simple setup is considered fail-safe and lightweight. However, the requirement that the cabin fits between the guideway and that the switch only works above a certain speed are drawbacks. Also, branching off or merging induces a jump in magnetic drag as well as vibrations when the EDS takes over. Depending on the chosen propulsion system, this can lead to a deceleration of the pod and reduced

passenger comfort for the duration of the lane switch. Theoretically, it is possible to switch horizontally with the same system and prevent the space requirement of the cabin by lowering only one side of the levitation system to EDS while keeping the other side of the EMS active. However, the transition to the secondary levitation system would have to happen at every lane switch and not only when merging or branching off, making it uncomfortable for passengers. Nevertheless, a combination of EMS and EDS is considered the best compromise for achieving a safe, lightweight lane switch at a high speed and high frequency without moving parts or the need for an infrastructure-heavy ceiling configuration. Therefore, this option was selected for this study.

- (D) This concept involves moving the suspension system laterally instead of featuring a secondary suspension system. The advantage here is that vertical switching is possible even at low speeds. However, a safe moving mechanism of the load-carrying suspension is considered complex, in addition to the restriction of being limited to vertical lane switching even at low speeds.

Choosing (C) appears to be the simplest and most realistic option for high-speed lane switching. Nevertheless, low-speed lane switches will also be necessary, and as the EDS requires a minimum speed, it is not functional in this regime. Passive, steerable wheels on the pod are one option to address this. However, passive rollers on the infrastructure side are considered for low-speed horizontal switches as an even simpler and more robust solution. Further details on this design are provided in Section 5.3.

4.4. Propulsion

To accelerate a vehicle to $600 \frac{\text{km}}{\text{h}}$, a special kind of linear motor is required. A short stator linear induction motor (LIM) is commonly used for low-speed maglev systems [13] but loses efficiency substantially at higher speeds due to end effects [22].

In addition to high speeds, high accelerations are also beneficial because the acceleration directly influences the required length of the on/off ramp to and the length required from the main lane. This is not a problem for point-to-point connections, but it has a large cost influence as soon as more than two stops are connected. This requirement is problematic for the Transrapid drivetrain, where a synchronous long stator uses the onboard levitation system as excitation. With this configuration, achieving accelerations greater than $1 \frac{\text{m}}{\text{s}^2}$ is challenging because of the coupling of levitation and propulsion.

Here, an air cored linear synchronous motor (LSM) long stator or a LIM long stator come into place, enabling the demanded $2 \frac{\text{m}}{\text{s}^2}$. While the LSM needs a strong excitation from either a permanent magnet array or a superconductor on board, there is no expensive lamination in the track necessary. The LIM long stator requires lamination but enables an adaption of the pole pitch and could theoretically even work with fixed frequencies for each track segment. Also, no heavy equipment is required on-board. A simple copper plate or bulk superconductors could be appropriate counterparts. What all of these solutions have in common is the long stator, meaning that the active part of the motor is in the track. Compared to a short stator, this reduces the flexibility during operation and increases the infrastructure costs. Additionally, a short stator is better in facilitating improvements with every pod iteration. But, it must be emphasized that a short stator propulsion instead of a long stator complicates the power supply, pod cooling, and the mass budget drastically.

Nevertheless, research [23] shows that a linear synchronous reluctance motor (synRM) is a plausible solution for a short stator with a maximum velocity of $600 \frac{\text{km}}{\text{h}}$ and a maximum acceleration of $2 \frac{\text{m}}{\text{s}^2}$. A major disadvantage of reluctance motors are force ripples, which have to be tackled with clever configurations and controlling algorithms. This configuration therefore seems to best fit the requirements to solve the power supply and cooling issues detailed in Sections 4.5 and 4.6.

For a long stator design, power supply and cooling are not as critical. One sensible consideration is therefore the use of a long stator LIM in booster sections and the use of a smaller-dimensioned short stator for low-speed alignment and maintaining speed. Still,

a substantial part of the track would have to facilitate boosters; therefore, if possible, the “all-in-one” short stator is preferable.

Table 4 presents the calculated propulsion requirements. Key inputs include values for aerodynamic drag and drag from the levitation system. The aerodynamic drag values are derived from a transient 2D axisymmetric simulation for a 10 mbar environment at 10 °C and are in accordance with the findings of Jang et al. [24]. An additional safety factor of 1.85 is included to reflect the 2D simplification [2]. In Section 5.1 the simulated values of blockage ratio (BR), will be utilized. The drag estimation for the levitation system is based on Sinha [20] for laminated homopolar EMS. These values are used to calculate the average energy demand. The maximum motor power required during acceleration is set at 3 MW.

Table 4. Propulsion characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Max motor power	3.00 MW
Drag BR 0.26 (max speed)	461 N
Drag BR 0.33 (nom speed)	557 N
Aero power (nom speed)	81.98 kW
Aero power (max speed)	76.78 kW
Drag from lev&guid	221 N
Power for lev&guid (nom speed)	32.50 kW
Mechanical motor power (nom speed)	114.48 kW
Electrical motor power (nom speed)	152.64 kW
Efficiency motor + energy transmission	75%
Power loss motor (nom speed)	38.16 kW

4.5. Power

To calculate the power demand of the pod, Table 5 considers not only the major contributors, propulsion and levitation, but also the power required for the onboard electronics in the passenger module (cabin systems) and in the service module (service electronics). As shown, a battery sized for the maximum power is sufficient to power the pod for about a quarter of an hour in nominal operation, according to the values of Higashimoto et al. [25].

Nevertheless, it is operationally unacceptable to charge pods in the stations. Firstly, space in the stations is limited, and it is detrimental if it is occupied by charging pods. Secondly, the amortization of pods is significantly improved when they are in operation most of the time instead of charging. Therefore, a continuous means of power transmission is required. The challenge is that this means of power transmission must be contact-free due to the high speed, and it must be relatively cheap as well as reliable because it is part of the infrastructure. Inductive power supply (IPS) is a technology developed for the Transrapid [26]. It is capable of transmitting power through magnetic resonance from a coaxial cable loop (primary) to a collector (secondary) in the pod. Although at peak times, for the roughly 180 kW nominal power per pod, the set $300 \frac{\text{kW}}{\text{km}}$ are insufficient when there are on average $2.25 \frac{\text{pods}}{\text{km}}$. This is seen as a meaningful compromise, as only after rush hour, some pods will have to charge. This means that it allows some pods to recharge in the stations after peak hours while generally enabling continuous operation.

Another driving factor influencing the total energy demand is the power required by vacuum pumps to counteract leakage, excluding the initial pump-down process. Table 6 summarizes the parameters of the vacuum system, indicating that with the leakage rate and power consumption observed in the 24 m Demonstrator, a pump station with 300 kW every 19.4 km would be sufficient to maintain the target pressure of 10 mbar. It is important to note that both the leakage rate and power consumption of the Demonstrator are conservative

measures. A significant portion of the leakage likely originates from the endcaps of the short Demonstrator tube, which are not fully representative, and the vacuum system is not operated at its optimal efficiency.

Table 5. Power characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Power cabin systems per seat	300 W
Power cabin systems	6.30 kW
Service electronics	5 kW
Nom power lev&guid	15.00 kW
Propulsion power at nom speed	152.64 kW
Total power for cruise at nom speed	178.94 kW
IPS required at peak per km	401.92 $\frac{\text{kW}}{\text{km}}$
Set IPS per km	300 $\frac{\text{kW}}{\text{km}}$
Max battery power	3,361,300 W
Power density lithium ion battery	2600 $\frac{\text{W}}{\text{kg}}$
Mass of the battery	1.29 t
Energy density of lithium ion battery	68 $\frac{\text{Wh}}{\text{kg}}$
Energy battery	88 kW h
Max travel time without IPS (nom speed)	29.41 min

Table 6. Vacuum characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Leakage rate Demonstrator	79.30 mbarL/s
Specific power consumption vacuum system Demonstrator	12 W/(m ³ /h)
Leakage per tube km	3478 mbarL/s
Required pump power per km	15,464 $\frac{\text{W}}{\text{km}}$
Pump power per station	300 kW
Distance between pump stations	19.40 km
Tube pressure	10 mbar
Passengers per year	8,000,000 $\frac{\text{pax}}{\text{yr}}$
Energy for vacuum per pax km	16.93 $\frac{\text{Wh}}{\text{pax km}}$

For the calculation of the average energy per traveled pax kilometer 8 Mio passengers per year were assumed. Additionally, the simplification was made that the system length is the same as the average trip length. This is true for point-to-point connections but must be analyzed further in detail for a hyperloop network.

Using the values given in Table 7, the average energy consumption at nominal speed can be calculated. The results show that even at 530 $\frac{\text{km}}{\text{h}}$ and with small pods, the energy demand of approximately 44 $\frac{\text{Wh}}{\text{pax km}}$ for the system can be considerably lower compared to that of high-speed rail (HSR) with 61 $\frac{\text{Wh}}{\text{pax km}}$ average at the European level according to Dalla Chiara et al. [27]. Here, the electrical power for cooling refers to the chillers required at the pumping stations to condense the vapor that was emitted by the pods for cooling (see Section 4.6). The losses of IPS consider the heat losses that are experienced on the track side. For HSR, the occupation is assumed to be 65% [27], but due to the smaller pods, a higher occupation is expected for the hyperloop system.

Table 7. Total energy characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Pod energy consumption per seat per km (nom speed)	14.20 $\frac{\text{Wh}}{\text{seat km}}$
Electrical power for cooling (condenser) per seat per km	1.27 $\frac{\text{Wh}}{\text{seat km}}$
Losses of IPS per seat per km	5.95 $\frac{\text{Wh}}{\text{seat km}}$
Occupation/seat usage	80%
Vacuum energy consumption per pax per km	16.93 $\frac{\text{Wh}}{\text{pax km}}$
Total power per pax per km	43.71 $\frac{\text{Wh}}{\text{pax km}}$

4.6. Cooling

Cooling presents a major engineering task for the hyperloop concept. Due to the low pressure, air cooling is only partially effective. Additionally, heat radiation is difficult to manage because creating a sufficient area with a large temperature difference is challenging. Heat storage is impractical for longer trips, as the required mass becomes unmanageable, and discharging the accumulated heat at the station can interfere with high-frequency passenger operations.

Therefore, sublimation or evaporation cooling, which is used in space applications with similar requirements [28], is proposed. The large enthalpy of the phase change offers a significant advantage in terms of mass. Additionally, the speed of sound in water vapor is higher than in air, improving the aerodynamic behavior. Nevertheless, several factors must be considered when designing the cooling system in detail.

The vapor released must be removed from the tube to prevent pressure increases. The volumetric flow resulting from the evaporation is substantial, making it inconvenient to handle with common vacuum systems. Instead, a condenser can be placed in front of the vacuum system. This arrangement allows the condenser to capture most of the water vapor, while the vacuum system handles the air leakages and the remaining moisture, thus reducing the load on the vacuum system considerably.

This method effectively transfers the required cooling power from the pod to the infrastructure, specifically to the chillers required for the condensers. It operates without issues as long as the outside temperature remains above a certain threshold. For water, the boiling temperature at 10 mbar is around 7 °C. Below this value, depending on the amount of air in the mixture, condensation can occur in the tube. Below 0 °C, ice will form on cold surfaces. This is not a problem for underground tracks, where temperatures do not reach such low values, but it can be problematic for above-ground tracks. Insulation of the tube can help, and coatings to prevent ice formation in certain areas of the tube are possible.

One way to completely resolve this issue is to lower the pressure to 1 mbar. At this pressure, only vapor exists down to a temperature of −20 °C, where it deposits in the form of ice. Sublimation, instead of evaporation, would be used on the pod, and cyclic ice condensers would be required instead of normal vapor condensers in front of the vacuum system.

Nevertheless, due to the large surface area of the tube, any forming ice or water will distribute well. For an average load of $8 \frac{\text{Mio pax}}{\text{yr}}$, a layer of less than 1 mm of ice would build inside the tube if temperatures remain consistently below 0 °C for an entire month. This is seen as acceptable and not worth the considerably higher effort for keeping a vacuum of 1 mbar and featuring ice condensers instead of vapor condensers. Consequently, a pressure of 10 mbar and evaporation cooling, possibly enhanced by some air cooling, was chosen. Inside the pod, heat is transferred to the evaporator via a liquid cooling circuit, enabling EMS levitation even at a standstill.

As shown in Table 8, even for a four-hour trip, the required mass of distilled water is reasonable, with approximately 371 kg. The amount of necessary water can be reduced

if auxiliary air cooling is utilized, particularly at high speeds and when the temperature inside the tube decreases during the winter season.

Table 8. Cooling characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Heat production per passenger	100 W
Heat from passengers	2.10 kW
Heat from lev&guid	13.50 kW
Heat from nom propulsion	38.16 kW
Heat from cabin systems	5.67 kW
Heat from service electronics	4.50 kW
Total heat load	63.93 kW
Evaporation cooling capacity	$0.00145 \frac{\text{kg h}}{\text{W}}$
Max travel time at nom speed	4 h
Worst-case water tank for evaporation	370.58 kg
Nom cooling requirement per pod per km	0.17 kg
Water release in average per day per km	$182.44 \frac{\text{kg}}{\text{d km}}$
Ice build-up per month (nom speed)	0.34 mm

4.7. Safety

Because the hyperloop system features a highly controlled environment, it is inherently safer than existing forms of transportation. Nevertheless, a thorough hazard analysis reveals some scenarios that require special consideration. A preliminary version of the safety concept presented here was reviewed by independent safety experts. Two major problems, safe real-time communication and the possibility to exit at every point of the tube, are avoided early on conceptually to guarantee a feasible and manageable safety concept. For better understanding, we present three core safety system functions that address all the identified hazard scenarios. Those system functions are illustrated in Figure 6 and are explained below:

- **Uncritical branch off:** In the event of medical issues or non-critical technical problems, the pod will branch off automatically at the next lane switch and enter the station nominally. The situation is handled by the complex operation control architecture, and no safety features are activated.
- **Forced branch off:** Critical failures in the pod, such as fire, operation control software issues, or a blocked track ahead can necessitate a forced branch off. In this case, the safety relay on-board cuts power to the levitation system shortly before the vertical lane switch, safely forcing a branch off. The pod will therefore branch off at every vertical lane switch and arrive at an emergency platform (marked red in Figure 7), where a gate seals the emergency platform once the pod has arrived. Following the repressurization of this segment, passengers can safely exit the pod. As shown in Table 9, an evacuation within 15 min, including 2 min for repressurization, can be guaranteed, even when lane switches are more than 100 km apart and due to the separate safety system, even in case of an operation control failure. If the segment ahead is blocked, all pods not fitting into the station will line up on the rescue lane, where safe exiting through doors is possible after repressurization. According to Table 9, such a rescue lane needs to be about 3.7 km long.
- **System failure handling:** In the event of a critical earthquake, a terror attack, or simultaneous failure of several subsystems, one track segment between two lane switches will be isolated with gates. All pods within this section will perform an emergency brake at $8 \frac{\text{m}}{\text{s}^2}$, featuring eddy current brakes. At the same time, the section

will be repressurized. This ensures that all pods can be brought to a safe state within one minute, from which they can await rescue. The rescue operation involves remotely controlled movement of the pods to the nearest stations and rescue teams for damaged pods. Table 9 also shows that the theoretical maximum number of passengers affected by an instantaneous breakdown is less than 150. Although the passengers are advised to remain seated, standing in the cabin is not prevented, which could lead to injuries during emergency braking.

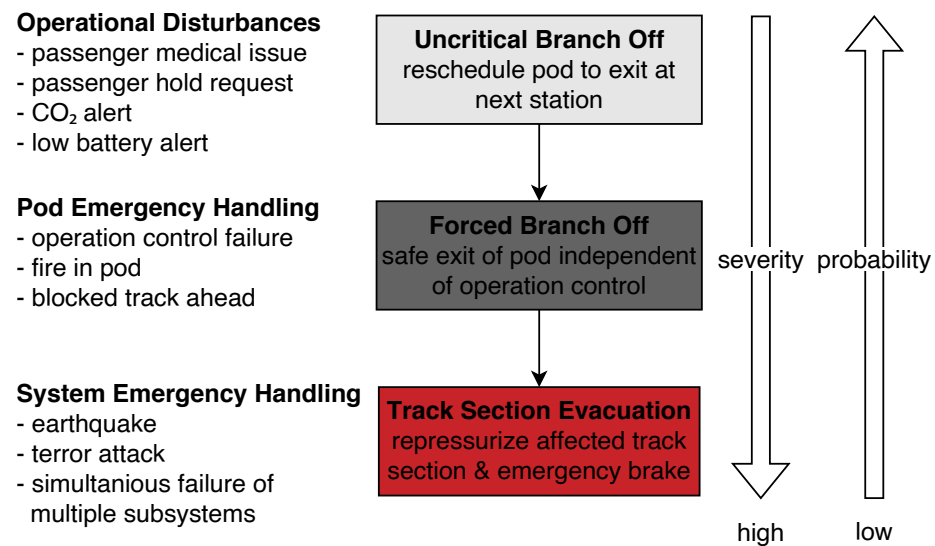


Figure 6. Schematic overview over the three major error procedures for safe handling of different hazard scenarios with their severity and probability.

Table 9. Safety characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Max time to hub	13 min
Max distance between hubs	109,327 m
Number of pods in this track segment	245.57 pods
Required rescue lane length	3684 m
Emergency acceleration	$8 \frac{m}{s^2}$
Braking length emergency	1736 m
Braking duration emergency	20.83 s
Max affected pods at sudden collapse (max speed)	6.89 pods
Max affected passengers at sudden collapse (max speed)	147 pax

Pressure loss in the pod is managed according to the leakage rate. To minimize disruption to operations while ensuring the safety of the passengers, one of the three previously mentioned error procedures is deployed based on the measured leakage rate and the resulting time constraint.

Gates are crucial to prevent the propagation of failures, effectively isolating sections of the tube to avoid the spread of issues due to a single error. Also, they allow for the extension of the main lane without filling the entire section with air. Manufacturing these large and heavy yet reliable mechanisms will be challenging but feasible. Inflatable rubber gates used in the pipeline industry present an interesting alternative but seem difficult to implement with the guideway geometry. Therefore, conventional steel gates have been chosen. Several sliding door designs have already been presented by the industry. For the

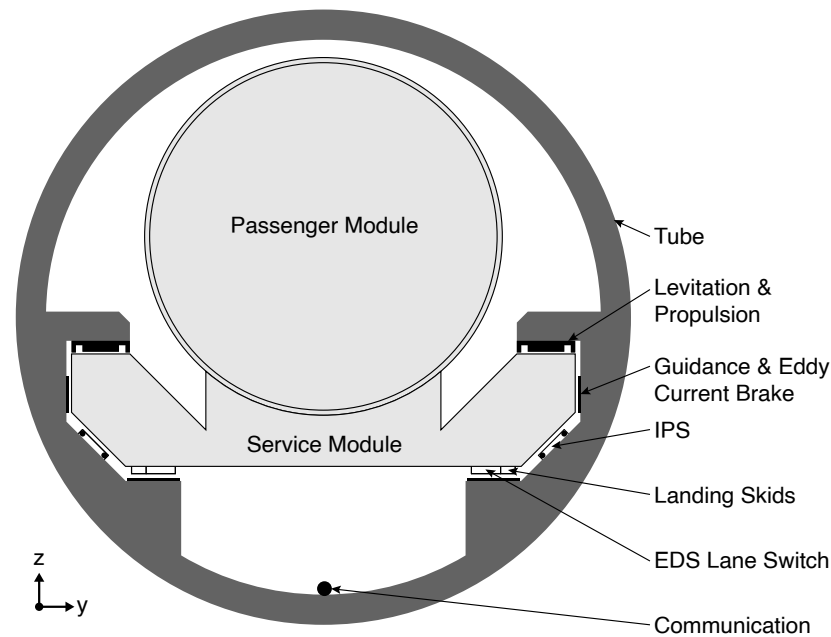


Figure 8. Cross-sectional sketch showcasing the interaction of the subsystems.

5.1. Infrastructure

While several components are necessary for seamless operation, including pumping stations, gates, lane switches, and operation control with the required servers, certified software, and sensory equipment along the route, the dominant part of the infrastructure is the tubes.

The tubes can be elevated, placed in a trench using dig-and-cover methods, or integrated into a tunnel. In all cases, crossing this infrastructure is easily feasible, and there is no noise pollution to the surroundings. Tunnels and bridges constitute a significant portion of the construction costs for ground-based infrastructure. Due to the optimized cross-section and distributed force introduction of the maglev system, both tunnels and bridges for the hyperloop system are expected to have considerable cost advantages when compared to their HSR alternatives.

Figure 9 provides the dimensions of the tubes required for different speed regimes based on aerodynamic considerations. The underlying BRs were selected to remain within the Kantrowitz limit at the corresponding speed. Even the full-speed tube requires less than half the space of a two-lane highway and enables more than double the throughput. Common single-lane train tunnels with a 9 m diameter occupy about 3.1 times as much volume as the nominal speed tunnel with a 5.1 m diameter.

Nevertheless, two tubes with an outer diameter of potentially up to 6 m are substantial in terms of visual impact, financial costs, planning, and land acquisition. Consequently, three options to reduce the tube cross-section are considered, each requiring further research:

- First, smaller tubes could be constructed, allowing pods to enter choked flow regions. Drag mitigation measures like lane switches or dedicated vacuum volumes as well as pressures as low as 1 mbar could help to keep the drag in bound. On the other hand, a long stator linear motor in these sections could handle the higher drag. Although this approach would result in a less energy-efficient system, it might be the overall better solution. However, the impact of expected aerodynamic phenomena, such as shock waves, on passenger comfort remains uncertain, requiring more research in this area.
- Secondly, a promising option is to accommodate both directions within a single tube or connecting both tubes to enable air flow between them. This would effectively reduce construction costs by nearly 50% and involve a relatively small BR, which is

only significantly reduced when pods pass each other. The primary concerns here would be noise and vibrations due to the passing pods.

- Thirdly, the concept of smaller pods without aisles, more akin to cars, is considered. An initial analysis indicates that for a capsule with an outer diameter of 1.6 m, a tube with an inner diameter of 3.5 m would suffice for nom speed, and 3.9 m would suffice for max speed. In this configuration, even the TUM Hyperloop Demonstrator tube would suffice for max speed. Although the throughput would decrease to $10,000 \frac{\text{pax}}{\text{h direction}}$ due to the increased number of pods, it would still be comparable to HSR. However, the main concern is passenger acceptance of the reduced space, necessitating further research.

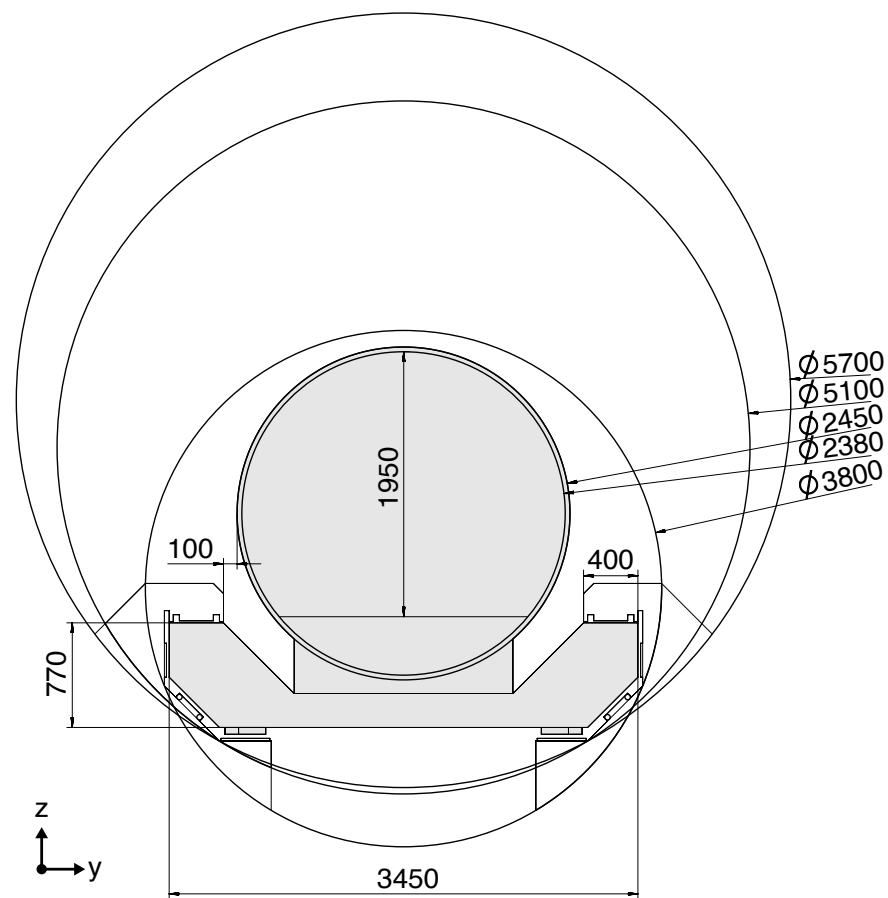


Figure 9. True-to-scale sketch of the cross section for the inside surface of the low-speed ($280 \frac{\text{km}}{\text{h}}$) tube with $\text{BR} = 0.62$, the nominal-speed ($530 \frac{\text{km}}{\text{h}}$) tube with $\text{BR} = 0.33$, and the full-speed ($600 \frac{\text{km}}{\text{h}}$) tube with $\text{BR} = 0.26$. The pod is colored in gray. Dimensions are given in millimeter.

Overall, during the next phases of development and detailed engineering of the system, keeping the tube diameter to a minimum will need to remain a key priority.

For the above-ground tubes, the choice of construction material is crucial. While welded steel tubes have demonstrated excellent gas tightness in the pipeline industry and simplify recycling, concrete tubes promise better scalability in series production, cost advantages, and better damping. Experiences with the TUM Hyperloop Demonstrator compared to other test facilities showed that the leakage rate of steel tubes is indeed better than for concrete. Nevertheless, at the targeted pressure level of 10 mbar, the observed leakage was acceptable, and the cost advantages outweighed the additional energy demand.

Additionally, a challenge for steel tubes is the load case. Pipelines operate with internal pressure, straining the material in tension. This scenario is reversed for hyperloop tubes, which are strained in compression, making concrete more suitable. One way to improve

the load case of a steel tube is corrugated steel. A concrete guideway with a corrugated steel shell, improving the critical buckling load case, was therefore investigated. However, complexities in the airtight connection between concrete and steel, as well as different thermal behaviors in sunlight, could not be justified by the achievable weight reduction.

Instead, a design with easily transportable prefabricated concrete parts was chosen. The low-speed tube is made of half shells, while the high-speed tubes are split into three optimized segments that are sealed against each other. These segments can be transported in containers or inside the system itself. The segments will be prestressed to form 20 m to 50 m tube sections. These sections will be lifted onto bearings mounted on pillars. After adjusting the position of the tube with the bearings, expansion joints will seal two segments flexibly but airtight. In Table 10, the mass of tube segments and a tube span of 35 m is estimated.

To realize curves, the ends of each segment will be milled slightly angled, and the curve will be approached with a polygon shape. Fixed banking will be integrated into the track by mounting the guideway tilted. The bearings are used to adjust the track in case of ground settlements.

Table 10. Tube characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Tube thickness	0.15 m
Inner tube diameter (max speed)	5.70 m
Cross-sectional area guideway (max speed)	0.93 m ²
BR (max speed)	0.26
Inner tube diameter (nom speed)	5.10 m
Cross-sectional area guideway (nom speed)	0.82 m ²
BR (nom speed)	0.33
Tube span (pillar distance)	35.00 m
Length of tube segment	2.50 m
Concrete density	2.30 $\frac{t}{m^3}$
Mass tube segment	21.19 t
Mass tube span	296.62 t

5.2. Pods

The pods consist of pressurized passenger or cargo modules mounted on service modules. The service module features most of the technical equipment, including the levitation, propulsion, and power supply system, while the passenger module runs the environmental control system and onboard electronics. A cargo module could be filled with pallets, Unit Load Devices (ULDs), or even a car.

Figure 10 shows a rendering of a possible seating configuration in economy class. The volumes opposite the two doors can be used for a toilet, a luggage rack, a wheelchair, or bicycles. Table 11 summarizes the dimensions of the pod and the cabin. The entire passenger or cargo module is transportable by truck or container and can be manufactured similar to the pressurized compartments of airplanes.

An important design decision is the aisle in the cabin. It is the driving factor for the diameter of the capsule and the tube. Without the aisle, every row of seats would require its own door, and an onboard toilet would be hardly possible. Additionally, the space helps create a comfortable atmosphere, which is crucial. Toilets could be excluded for shorter trips but are considered. People with reduced mobility are accommodated in boarding, seating, and emergency procedures.



Figure 10. Rendering of a pod with maximum packaging for 21 passengers plus one person with reduced mobility in an isometric view (A) and front view (B).

Table 11. Pod dimensions.

Description	Value
Seats per pod	21
Cabin height (at aisle)	1.90 m
Seat width	0.46 m
Seat pitch	0.86 m
Passenger module outer diameter	2.50 m
Cabin length	9.00 m
Pod length	12.00 m
Pod cross-sectional area	6.47 m ²

The life support system of the passenger module cannot rely on bleed air like planes. Therefore, CO₂ scrubbers and HEPA filters will be integrated into the air conditioning system. Refillable oxygen bottles will compensate for the breathing of passengers. Pressure fluctuations will be controlled using an additional pressurized air bottle.

Table 12 provides a feasibility check of the pod mass budget in absolute and relative numbers. Additionally, the mass of the distributed systems is divided by 14 (7 boogies with two drivetrain modules each) to see the mass budget per module.

Table 12. Pod mass breakdown. Values with a grey background are calculated, while others are input values.

Description	Relative Value	Absolute Value	Value Per Module
Passenger + baggage per seat		100 kg	
Passenger + baggage total		2100 kg	
Interior + life support per seat		70 kg	
Interior + life support total		1470 kg	
Payload	23.8%	3570 kg	
Fairing	3.3%	500 kg	
Pressure vessel structure	15.3%	2300 kg	
Cooling	4.7%	700 kg	
Service module structure	6.7%	1000 kg	
Electronics (inverter, harness, communication, control)	6.7%	1000 kg	71 kg
Battery	9.3%	1400 kg	100 kg
EDS	3.7%	550 kg	39 kg
IPS	1.9%	280 kg	20 kg
Propulsion	6.0%	900 kg	64 kg
Levitation	18.7%	2800 kg	200 kg
Total pod mass		15,000 kg	

5.3. Stations

As mentioned in Section 4.3, low-speed switching is problematic for the chosen EDS lane switching mechanism, which requires moving parts in the station. The following section explains the three station layouts presented in Figure 11.

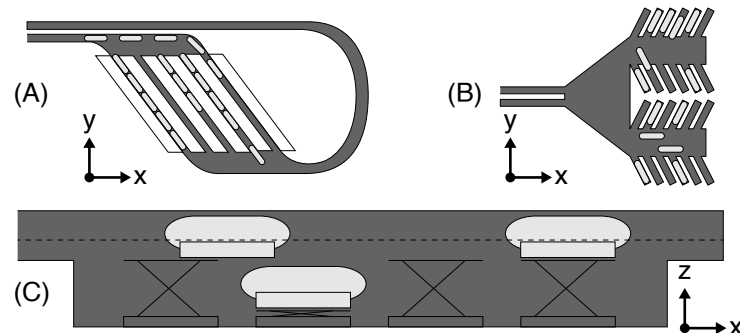


Figure 11. Schematic drawing of three different station layouts. (A) Lung design with moving rollers in the low-speed switch. (B) Autonomous crawler station. (C) Scissor lift design for small and compact stations.

- (A) For larger cities, the lung-shaped design enables high throughput. Table 13 outlines the possible characteristics of a large station. In this design, low-speed horizontal switching is realized by cylindrical rollers in the floor. Due to the number of rollers, the failure of individual wheels does not significantly affect operation. The minimal curve radius the pod can handle is decisive for the scale of this layout.
- (B) Initially, presumably better-suited for cargo stations, the pod could also land on an autonomous driving crawler, bringing the pod to boarding and back. This design is the most compact and flexible, but guaranteeing the reliability of the wheeled systems in a vacuum is challenging.
- (C) For smaller stations, where a compact linear design is favorable, the pods can land on scissor lifts, lowering them and freeing the tube during boarding. After that, the pod is lifted back up to start the trip. Hydraulic cylinders and the simple mechanism are expected to work reliably, even in a vacuum.

Table 13. Station characteristics. Values with a grey background are calculated, while others are input values.

Description	Value
Station throughput	10,000 $\frac{\text{pax}}{\text{h}}$
Transition time	8 min
Pods leaving/arriving per min	7.94 pods/min
Min time distance between pods	7.56 s
Pods in station	63.49 pods
Min total platform length	761.90 m

In addition to passenger and cargo stations, there will be maintenance stations for regular cleaning and check-ups of the pods. Parking stations outside the city might be necessary to compensate for changing, direction-dependent demand.

6. Conclusions

This study presents a coherent technical concept for a hyperloop system, demonstrating the feasibility of integrating various functions into a viable transportation solution.

An iterative approach was featured to tackle the complex, interdependent system requirements and the large solution space. A single source of truth methodology en-

sured convergence towards a sensible solution that is capable of fulfilling the challenging requirements.

Key design decisions were made to optimize performance and cost-efficiency. These include setting the maximum speed at $600 \frac{\text{km}}{\text{h}}$ with a capacity of 21 passengers per pod, utilizing air docks instead of air locks, implementing EMS with EDS for high-speed lane switching, and using short stator motor technology. Additionally, the system employs evaporation cooling at 10 mbar, a 300 kW IPS system, and a safety concept that avoids doors along the entire track. Prefabricated concrete parts are used instead of steel for the tube construction. Considering all factors, the energy demand per passenger is calculated to be considerably lower than for HSR.

Optimizing for other targets can result in different designs. For example, in countries with large cities that are more than 500 km apart with relatively empty spaces in between, it could be beneficial to implement a long stator, longer pods, and speeds of up to $900 \frac{\text{km}}{\text{h}}$.

The main engineering challenges identified include the detailed design and testing of the synRM and IPS systems, as well as developing reliable communication systems and testing of the high-speed lane switch. Further challenges involve tube design including the guideway alignment and ensuring safety with short headways. For the pods, the snake mechanism to enable small-curve radii and rigorous mass budgeting requires focus.

In conclusion, this study offers a comprehensive framework for future hyperloop development, encouraging further research and standardization efforts within the community.

Future research is required, especially in the areas of hyperloop aerodynamics, cost-efficient tube construction, safe real-time communication, and the EMS–EDS hand-over for lane switching. Conceptual investigations have to be validated via actual high-speed testing. The next steps include the detailed technical design of all subsystems, the development of widely accepted norms and safety regulations, dissemination to inform the public, and gathering of financial support for necessary further research and test tracks. Open alignment discussions between teams working on hyperloop technology to support standardization are encouraged.

The findings demonstrate that a well-integrated hyperloop system can significantly enhance transportation efficiency and sustainability, offering a promising extension to traditional modes of travel.

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Abbreviations

BR	blockage ratio
EDS	electrodynamic suspension
EMS	electromagnetic suspension
HSR	high-speed rail
IPS	inductive power supply
lev&guid	levitation and guidance
LIM	linear induction motor
LSM	linear synchronous motor
max	maximum
nom	nominal
synRM	synchronous reluctance motor
TSB	Transport System Bögl
TUM	Technical University Munich
ULDs	unit load devices

References

- Lang, A.J.; Connolly, D.P.; de Boer, G.; Shahpar, S.; Hinchliffe, B.; Gilkeson, C.A. A review of Hyperloop aerodynamics. *Comput. Fluids* **2024**, *273*, 106202. [\[CrossRef\]](#)
- Radeck, D.; Nicolau, J.; Kukharskii, V.; Guerra, L.O.; Herkenrath, F.; Martínez, I.V.; Pflüger, J.; Jocher, A.; Breitsamter, C. Drag Dependency Aspects in Hyperloop Aerodynamics. *Aerosp. Sci. Technol.* **2024**.
- Schiefer, P.; Kleikemper, O.; Holzapfel, F. Modeling of Coupled Electric and Magnetic Circuits in Electromagnetic Suspension Vehicles. *IEEE Trans. Transp. Electr.* **2024**. [\[CrossRef\]](#)
- Hedhly, W.; Amin, O.; Shihada, B.; Alouini, M.S. Hyperloop Communications: Challenges, Advances, and Approaches. *IEEE Open J. Commun. Soc.* **2021**, *2*, 2413–2435. [\[CrossRef\]](#)
- Kirschen, P.; Burnell, E. Hyperloop system optimization. *Optim. Eng.* **2023**, *24*, 939–971. [\[CrossRef\]](#)
- Decker, K.; Chin, J.; Peng, A.; Summers, C.; Nguyen, G.; Oberlander, A.; Sakib, G.; Sharifrazi, N.; Heath, C.; Gray, J.S.; et al. Conceptual feasibility study of the hyperloop vehicle for next-generation transport. In Proceedings of the AIAA SciTech 2017, Grapevine, TX, USA, 9–13 January 2017;
- Nøland, J.K. Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review. *IEEE Access* **2021**, *9*, 28439–28458. [\[CrossRef\]](#)
- Hansen, I.A. Hyperloop transport technology assessment and system analysis. *Transp. Plan. Technol.* **2020**, *43*, 803–820. [\[CrossRef\]](#)
- Deng, Z.; Zhang, W.; Zheng, J.; Wang, B.; Ren, Y.; Zheng, X.; Zhang, J. A High-Temperature Superconducting Maglev-Evacuated Tube Transport (HTS Maglev-ETT) Test System. *IEEE Trans. Appl. Supercond.* **2017**, *27*, 1–8. [\[CrossRef\]](#)
- Hardt Hyperloop. Hyperloop Progress Paper. Technical Report, 2023. Available online: <https://www.hardt.global/s/2023-08-11-Hyperloop-Progress-Paper-V11.pdf>. (accessed on 4 November 2024).
- Pareschi, G.; Ehwald, J.; Leng, N.; Beckert, P.; Guo, B. *Potential Analysis for Vacuum Transport Technologies in Public Transport in Switzerland: Life-Cycle Analysis with Focus on Energy Consumption and Environmental Impact of a Vacuum Transport Infrastructure*; Federal Office of Transport FOT: Bern, Switzerland, 2023; [\[CrossRef\]](#)
- Schach, R.; Jehle, P.; Naumann, R. *Transrapid und Rad-Schiene- Hochgeschwindigkeitsbahn*; Springer: Berlin/Heidelberg, Germany, 2006. [\[CrossRef\]](#)
- Zamzow, B.; Mnich, P.; Fritz, E.; Bögl, S. A Novel Automated Urban Maglev Transport System—Actual Design and Operational Data Compared with Legacy SysEMS. In *Automated People Movers and Automated Transit SysEMS 2018*; American Society of Civil Engineers: Reston, VA, USA, 2018; pp. 176–184. [\[CrossRef\]](#)
- Radeck, D.; Hsu, F.H.M.; Janke, F.; Semino, G.; Hofmann, T.; Rink, S.; Jocher, A. Propulsion and Suspension Concept of the Technical University of Munich Hyperloop Full-Scale Demonstrator. *Appl. Syst. Innov.* **2024**, *7*, 19. [\[CrossRef\]](#)
- Kossiakov, A.; Sweet, W.N.; Seymour, S.J.; Biemer, S.M. Concept Definition. In *SysEMS Engineering Principles and Practice*; Sage, A.P., Ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2011; Chapter 8, pp. 197–253. [\[CrossRef\]](#)
- Watson, I. High-Speed Railway. *Encyclopedia* **2021**, *1*, 665–688. [\[CrossRef\]](#)
- Kalsi, S.S. *Applications of High Temperature Superconductors to Electric Power Equipment*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
- Han, H.S.; Kim, D.S. Magnetic levitation. In *Springer Tracts on Transportation and Traffic*; Springer: Dordrecht, The Netherlands 2016; Volume 247. [\[CrossRef\]](#)
- Leng, P.; Li, J.; Jin, Y. Kinematics modeling and analysis of mid-low speed maglev vehicle with screw and product of exponential theory. *Symmetry* **2019**, *11*, 1201. [\[CrossRef\]](#)
- Sinha, P.K. *Electromagnetic Suspension Dynamics & Control*; Peter Peregrinus Ltd.: London, UK, 1987.
- Usman, I.; Jedinger, A.; Hansl, M. Vehicle-Based Guided Switching. U.S. Patent US11554796B2, 3 September 2019.
- Selcuk, A.H.; Kurum, H. Investigation of End Effects in Linear Induction Motors by Using the Finite-Element Method. *IEEE Trans. Magn.* **2008**, *44*, 1791–1795. [\[CrossRef\]](#)

23. Cao, R.; Su, E.; Lu, M.; Si, J.; Wang, K. Investigation of linear synchronous reluctance motor for urban rail transit. *IET Electr. Power Appl.* **2020**, *14*, 41–51. [[CrossRef](#)]
24. Jang, K.S.; Le, T.T.G.; Kim, J.; Lee, K.S.; Ryu, J. Effects of compressible flow phenomena on aerodynamic characteristics in Hyperloop system. *Aerosp. Sci. Technol.* **2021**, *117*, 106970. [[CrossRef](#)]
25. Higashimoto, K.; Homma, H.; Uemura, Y.; Kawai, H.; Saibara, S.; Hironaka, K. Automotive lithium-ion batteries. *Hitachi Rev.* **2011**, *60*, 17–21.
26. Bauer, M.; Becker, P.; Zheng, Q. Inductive power supply (IPS[®]) for the transrapid. In Proceedings of the MAGLEV 2006: The 19th International Conference on Magnetically Levitated Systems and Linear Drives, Dresden, Germany, 13–15 September 2006; pp. 13–15.
27. Dalla Chiara, B.; De Franco, D.; Coviello, N.; Pastrone, D. Comparative specific energy consumption between air transport and high-speed rail transport: A practical assessment. *Transp. Res. Part D Transp. Environ.* **2017**, *52*, 227–243. [[CrossRef](#)]
28. Chang, K.; Wang, Y.Y.; Li, Y.Z. A review of water sublimation cooling and water evaporation cooling in complex space environments. *Prog. Aerosp. Sci.* **2023**, *140*, 100930. [[CrossRef](#)]

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