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Lists of Acronyms

Acronym	Meaning
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CSM	Safety Common Methods
EMC	Electro-Magnetic Compatibility
EMS	Electromagnetic Suspension
ERA	European Railway Agency
HSR	High Speed Rail
HST	High Speed Train
LIM	Linear Induction Motor
LRM	Linear Reluctance Motor
LSM	Linear Synchronous Motor
RAMS	Reliability, Availability, Maintainability and Safety
SIL	Safety Integrity Level
TRL	Technical Readiness Level
WP	Work Package

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1 Executive summary

The present Deliverable summarizes the research activity developed within the Work Package 3 Technical Definitions, where the technical information available, which will allow depicting different scenarios that may arise during the start-up process of Hyperloop. This includes safety and operational visions considering what is possible to accept and adapt from rail knowledge, the common technical core and challenges within interoperability as a service concept, the identification of hazards, standardization roadmap and convergences with ongoing programs in other transport modes. Concept of operation and standard operating procedures focused on the integration in control and management for service providers.

This deliverable is the second public document of HYPERNEX project and corresponds to the work made in the third work package WP3 “Technical definitions” led by DICEA (Italy)

The Deliverable is composed of four sections, respectively dealing with: 1) innovative concepts suitable for guided transport modes; 2) hazards identification and safety cases analysis; 3) technical components of Hyperloop architecture; 4) Hyperloop operation concept.

Section 1 explores innovative guided transport modes and examines their architectural, functional and legislative aspects. The guided transport concepts explored in the task include Hyperloop, Maglev, Aviation and High-Speed Rail. Different use cases of transport modes, such as freight or passenger, were touched upon. Towards a more numerical approach, a scalability analysis consisting of capital and operational expenses analyses has been conducted and an overview of transport innovations has been articulated. Moreover, an analysis focused on the past and future developments of guided transport modes has been compiled. More energy efficient transport alternatives have been also explored, including concepts, such as hydrogen or battery trains. Finally, an overview of regulations and standardizations on innovative rail technologies have been sketched.

Section 2 deals with safety approaches from Safety Common Methods (SCM) and EN 50126 schemes, essential to develop a hazard log regarding technological framework, safety integration, operational performances and evacuation, including persons with reduced mobility, and human exposures to Hyperloop activity, cybersecurity, etc. Safety case analysis has been carried out in accordance with the fields mentioned above and closely related to technical components. A generic Hyperloop system has been analysed and discussed. Hazards common to all Hyperloop solutions have been described and classified mainly based on evaluations of probability and consequences. A hazard log has been included in Annex 2, listing all the different hazards together with relevant mitigations and their risk classes. A wide-ranging hazard analysis has been performed and the safety case approach has been described. Finally, future research needs have been identified.

Section 3 analyses technical elements of the Hyperloop systems’ architecture and subsystem components. There are several steps taken towards reaching consensus on systems architecture, mainly utilizing the system engineering principles. Moreover, there are a number of innovative

concepts being developed within the transportation sector based on the information and communication technologies, such as artificial intelligence or virtual coupling. Such technologies can be applied to Hyperloop as well. The most promising among these concepts have been highlighted in this chapter as well. A number of further research areas have been identified, such as the integration of Hyperloop into current and future spatial planning policies and with other transport modes and their networks, e.g. rail stations, airports, etc., for cargo transport as well, the analysis of linear, non-linear, static, dynamic and buckling behaviour of the pipes, the optimal tube diameter, the tunnel infrastructures that would reduce environmental impacts, the most appropriate acceleration and deceleration profiles, the applicability of the existing communication systems for Hyperloop low pressure and high speed environment, vehicles platooning and best headways in relation to safety as well as capacity and comfort of passengers.

Section 4 proposes a concept of operations for future tube transportation systems designed to facilitate intermodal connections with other passengers transport systems and freight delivery services. The specifications should be defined by local transportation regulators and standardization bodies. It is preferable to minimize any impact on the surrounding environment and on nearby communities. Safety has to be incorporated into the design of the system, such as headways to ensure they have adequate braking space in the event of failures or other emergencies. This will include the ongoing monitoring of real-time data and other risk assessment measures. Finally, the systems must be designed so that they can be maintained using practical and cost-effective procedures, to keep them in good working order and ensure that the safety is maintained. The design should also consider a safe decommissioning at the end of the lifetime, using practical and cost-effective procedures, either to be rebuilt and renewed or for the corridor to be rebuilt in a different form, replaced for a different purpose or the land restored to its original condition.

2 Innovative concepts for guided transport modes

2.1 Introduction

Guided transport is a transport system in which designated vehicles move on a previously determined trajectory for all parts of their journey (Furlan, Schmidt, 2011). Guided transport modes include transport types such as railways, tramways, or monorails (Nehashi, 2001). In the last 20 years, guided transport has been developing rapidly, with organizations working on innovative developments in the sector constantly.

The following chapter aims to explore concepts and ideas, which, through their innovative nature, may be applied in guided transport. While the previous Deliverable 2 mapped out the extent of Hyperloop capabilities, this section of the document aims to go beyond the previously established consensus and take a closer look at other innovations and solutions alongside Hyperloop.

2.2 Innovative concepts

2.2.1 Types of guided transport modes

Below, several types of guided transport modes will be enumerated and briefly described, to provide a clear understanding of the studied subject matter.

2.2.1.1 Hyperloop pax

Hyperloop is an ultra-high speed transport system ($v > 800$ km/h). The main distinguishing feature of this system is the fact that the Hyperloop capsules will move in a dedicated tubular artery with a very low-pressure inside (max 0,001 atm). Vehicles can travel at ultra-high speeds with low energy expenditure due to a significant reduction in aerodynamic drag. (Doppelbauer, 2018).

Hyperloop is currently being developed by several commercial companies and research centers. There are several proposed solutions for the propulsion and suspension systems. In most cases, the electric linear motor drive is considered for propulsion. Depending on the design, the powered part of the motor is either in the vehicle or on the track. There is also contemplated a propulsion system which is based on a fan and an air compressor. Suspension systems in most cases are magnetic and they can be Electro-Dynamic Suspension (EDS) or Electro-Magnetic Suspension (EMS).

2.2.1.2 Maglev

Maglev is a magnetic transport system for medium (120-250 km/h) and high speeds (250-500 km/h) (Doppelbauer, 2018). Vehicles move in the open air on a dedicated track without any mechanical contact with the track. Maglev railways are mostly propelled by electric Linear Synchronous Motors (LSM) or by Linear Induction Motors (LIM). In most cases, the EMS is used for levitation and guidance. There are many implementations of Maglev all over the world, e.g.

Shanghai Transrapid (motor: LSM; levitation: EMS; max speed: 431 km/h; route length: 30.5 km) or Incheon Airport Maglev (motor: LIM; levitation: EMS; max speed: 110 km/h; route length: 6.1 km). Also Maglev can be used for metropolitan areas reaching up to 150 km/h with a capacity similar to the metro with less investment cost (Boegl, 2021).

2.2.1.3 PRT

PRT is a low-speed personalized urban or suburban transport system ($v < 50$ km/h). A single-vehicle travels on dedicated routes and can carry 2-3 persons. The propulsion system can be both a rotating and a linear electric motor. The PRT system does not use magnetic suspension systems. An example of a functioning PRT system is ULTRA at Heathrow airport, where it has replaced a certain section of the airport bus service. There are 21 vehicles on the 3.9 km long route. These vehicles are able to move with a max speed of 40 km/h.

2.2.1.4 Magrail

Magrail is a high speed transport system ($v > 250$ km/h). The vehicles will be propelled by a linear electric motor and will be equipped with a magnetic EDS system. The vehicles will move along the existing railway corridors. Magrail will use the conventional railway infrastructure for operation, with an added magnetic infrastructure for propulsion and suspension. Magrail infrastructure elements will be installed respecting the railway gauge. The system is currently being developed by NEVOMO and will be tested on a full-scale experimental track in 2022.

2.2.2 Technological and architectural vision

Technologies which may be applied to such a guided transport system, e.g. Hyperloop, Maglev or Magrail, are strictly dependent on the use case i.e. for medium-speed high-load cargo system different propulsion and suspension solution would be applied than for high-speed mainline passenger transport. There are three main types of linear propulsion systems, described here below.

- Permanent Magnet Linear Synchronous Motor (PMLSM) consisting of 2 parts moving relatively to each other. The primary part consists of 3 phase windings, while the secondary is equipped with permanent magnet systems. The energized windings generate an alternating magnetic field that interacts with the constant magnetic field caused by the permanent magnets. By appropriately controlling frequency and voltage of the windings supply, the magnetic field begins to travel along the length of the motor, thus producing a synchronous relative motion between mover and stator. Depending on the configuration, the windings can be stationary and placed in the track along the entire route (long-primary motor) or it can be moving and placed on the vehicle (short-primary motor).
- Linear Induction Motor (LIM) consisting of 2 parts moving relatively to each other. The primary part consists of 3 phase windings, while the secondary is made of an aluminium plate laid on a ferromagnetic yoke. The energized windings generate an alternating

magnetic field, which induces Eddy currents in the aluminium layer. This creates an opposing magnetic field from the Eddy currents, which repels with the traveling field of the windings. By appropriately controlling frequency and voltage of the windings supply, the magnetic field starts to move along the length of the motor, thus producing an asynchronous relative motion between mover and stator. Depending on the configuration, the windings can be stationary and placed in the track along the entire route (long-primary motor) or it can be moving and placed on the vehicle (short-primary motor).

- Linear Synchronous Reluctance Motor (LSRM) consisting of 2 parts moving relatively to each other. The primary part consists of 3 phase windings, while the secondary is made of specially formed layers made of soft magnetic material and magnetic barriers, the shape of which is to allow the most natural flux distribution. When energized, the windings generates a magnetic field penetrating the ferromagnetic secondary. The moving part under the influence of the flux strives to position itself to provide a path with the least possible reluctance. By appropriately controlling frequency and voltage of the windings supply, the magnetic field starts to move along the length of the motor, thus producing a synchronous relative motion between mover and stator. Depending on the configuration, the windings can be stationary and placed in the track along the entire path (long-primary motor) or it can be moving and placed on the vehicle (short-primary motor).

For suspension systems there are also three typologies, describe here below.

- Electro-Dynamic Suspension (EDS) systems, whose principle of operation is based on electro-dynamic interactions, with a source of the magnetic field (e.g. permanent magnet or electromagnet) and a conducting element (e.g. aluminium plate). During their relative motion, the moving magnetic field induces Eddy currents in the conducting element, which as they flow interact with the forcing magnetic field. The result is a force acting on both elements that have two main components. A levitation or guiding force, repelling the two elements from each other, and a magnetic braking force are created.
- Electro-Magnetic Suspension (EMS) levitation and guidance systems, e.g. used in Maglev. The classical system is based on the magnetic force between an unpowered ferromagnetic element and a ferromagnetic element with a wound coil. By properly energizing the windings of the electromagnet, an attractive force is created between the two elements as a result of a common flux flowing through them. These systems can be equipped with permanent magnets to increase the energy efficiency of the system. In most Maglev rail suspension systems, a passive ferromagnetic element is mounted in the track, while the vehicle is equipped with electromagnets.
- Wheels, the basic suspension type based on physical interface between the vehicle and the infrastructure.

2.2.3 Functional vision

Guided transport modes may be designed to specific purposes.

2.2.3.1 Passenger use case

When it comes to applying guided transport modes for passenger, we can distinguish it into two categories: regional and intercity transport.

In regional passenger transport, it is understood that this covers mainline traffic covering the distance of approximately 200 km, with vehicles which can achieve around 150-200 km/h. This type of transport can be primarily used for connections within the same region.

For intercity transport, the distance considered is much bigger, anything above 200 km. This can be used primarily for intercity connections. Because of the potential of guided transport modes to achieve ultra-high-speeds of up to 550-1000 km/h, the time of journey is significantly reduced.

2.2.3.2 Freight use case

Guided transport modes can be alternatively applied to carry cargo. Similarly to passenger use case, in the case of freight transport we can also distinguish connections in two categories according to distance and speed: regional (low/medium speeds) and intercity connections (ultra-high speeds).

Additionally, freight transport can be distinguished by looking at its loading capacity. On one hand, there is small cargo, e.g. used in e-commerce where there is a pressing need for instant parcel delivery, freight transportation can be used as an alternative or alongside traditional postal companies.

On the other hand, freight transport can be considered as a solution with a high loading capacity. In this case, 20-40 ft containers can be carried both on medium and long distance connections. Containers can be either transported from hub-to-hub (e.g. from one logistic center to another one) or alternatively they can be tailored for special purpose transit as requested by the client.

Indeed, cargo is a very heterogenic market, with a wide range of different highly specialized segments (e.g. pharmaceutical, perishables and dangerous goods), which could create relevant opportunities for freight Hyperloop as well as some additional safety issues for operation.

2.3 Analyses of Hyperloop innovative concepts

2.3.1 Scalability analysis

Although the concept of vacuum train can be dated back to the 19th Century, it was more recently that the idea gained on popularity, after being promoted by popular inventor Elon Musk. Upon its publication in 2013, the low costs included in the *Hyperloop Alpha* white paper (Musk, 2013) attracted a great deal of media attention. *Hyperloop Alpha* estimated a cost of 6 billion USD for

the passenger-only version system, less than 1/10 of the cost for the California High Speed Rail (CAHSR), and then estimated at 68.4 billion USD. The study cited superb energy efficiency, which can be observed in Figure 1.

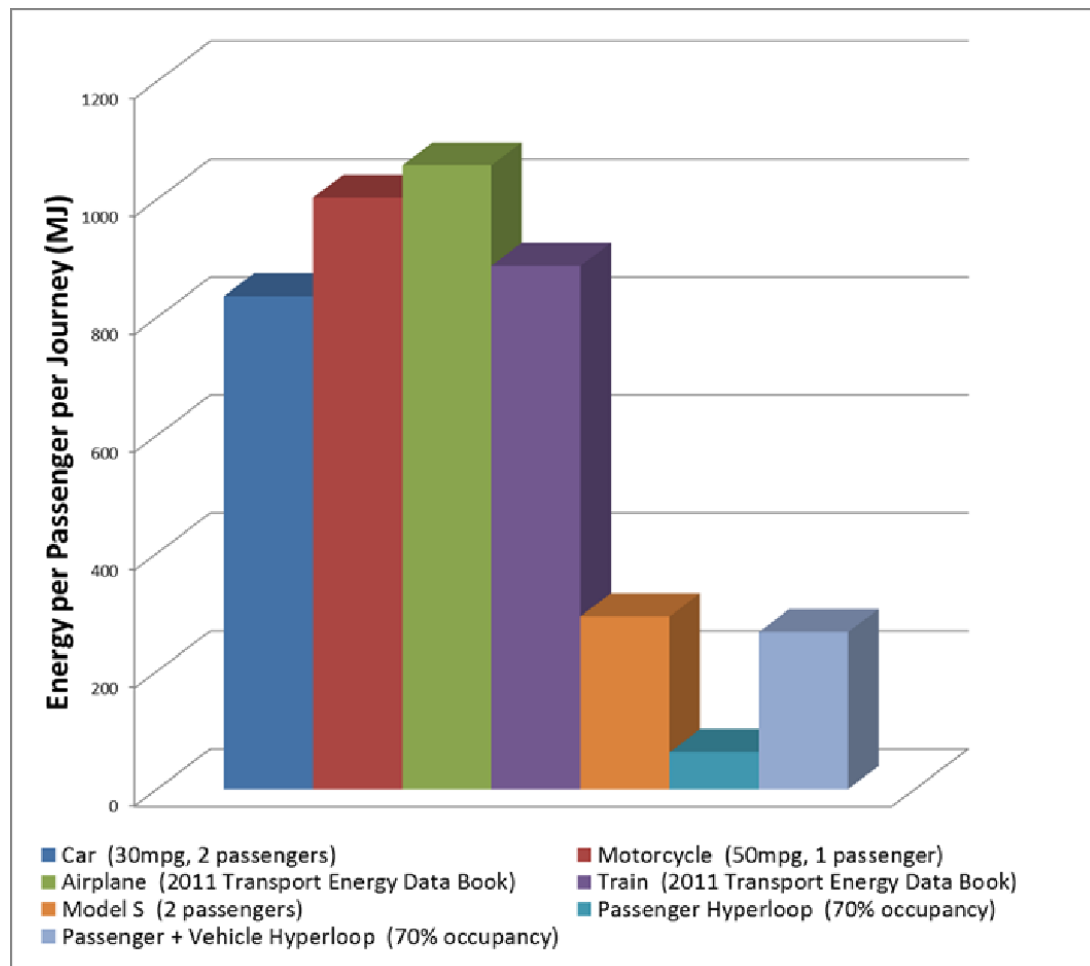


Figure 1. Energy cost per passenger for a journey between Los Angeles and San Francisco for various modes of transport. Source: (Musk, 2013)

The authors encouraged members of the innovators community to contribute to the Hyperloop design process, saying that iteration of the design by various individuals and groups can help bring Hyperloop from an idea to reality. Since then many people have responded, some of them inspired by the idea, others criticizing the over-optimism and under-estimation of costs (Hansen, 2020) (Taylor, Hyde, Barr, 2016).

As the technology is slowly reaching higher Technical Readiness Level (TRL), there is an increasing number of papers trying to capture the latest development in the domain and to structure the knowledge we have so far (Nøland, 2021). It has been concluded that majority of the publications focus on performance aspects, such as safety (35%), energy (33%) and cost (30%). (Mitropoulos, Kortsari, Koliatos, Ayfantopoulou, 2021). Figure 2 displays the different Hyperloop research areas.

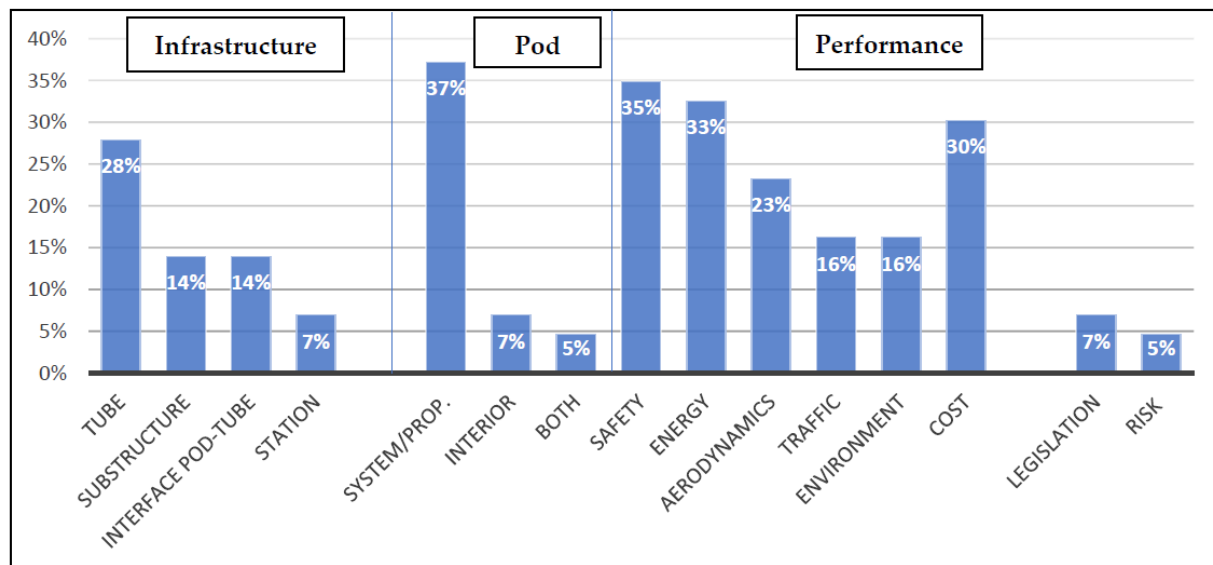


Figure 2. Hyperloop EU research areas. Source: (Mitropoulos, Kortsari, Koliatos, Ayfantopoulou, 2021)

2.3.2 Tube construction

The tube is to be prefabricated offsite and positioned on the pylons. The cost estimate is based on two tubes roughly 3 m in diameter. Increasing the number of tubes or the tube diameter would increase the total tube cost. Indeed, a 3 meter diameter tube for the Alpha estimate would not be large enough for standard 10 ft shipping container, which shows how outdated these costs estimates are, given that the active firms announced they will focus on freight initially. Moreover, the cost of the tube should include isolation requirements and welding that is unclear if it is included into the original costs estimation.

2.3.2.1 Pylon construction

The *Hyperloop Alpha* estimated 25,000 concrete pylons along the route. Their cost may increase if more tubes are added. One critique suggested that the pylons would need more robust seismic dampers than described in the proposal, which would significantly raise costs.

2.3.2.2 Tunnel construction

The *Hyperloop Alpha* proposal estimated 50 million USD per mile of tunnel. The cost estimate is based on two tubes roughly 3 m in diameter. Increasing the number of tubes or the tube diameter would increase the unit tunnel cost. *Hyperloop Alpha* estimates roughly 15 miles of total tunnel length but routing changes could change this figure.

2.3.2.3 Station and vacuum pumps

Hyperloop Alpha estimated station construction costs at 125 million USD. The conceptual station locations were outside the urban cores, both in San Francisco and Los Angeles and stations construction would be more expensive in an urban location. If more tubes are added, station and vacuum pump costs would increase to handle greater capacity. Adding intermediate stations or alternate branches would similarly increase station costs.

2.3.2.4 Vehicle

The costs for purchase of a vehicle capsule were estimated in (Musk, 2013) to be about 1.42 million USD. These costs are for a capsule without toilets. In order for a capsule to be equipped with a toilet, additional 1.52 USD is expected to be added to the cost. However, the estimations made in the white paper (Musk, 2013) were shown to be largely too low, when comparing the prices to a carriage of a Maglev train (Van Goeverden et al., 2018), which indicated that the assumed cost of a capsule is 4.8 million USD. This number is more than the threefold of the above-mentioned estimation by Musk.

2.3.2.5 Permits and land

Land costs have potential to be substantially higher than estimated by *Hyperloop Alpha*. It suggests that by building the system on pylons, land owners will be willing to sell overhead access and pylon rights for lower prices than is needed for a ground level high-speed rail system. However, High Speed Railways (HSR) could also be built on pylons and project planners did not pursue that option, suggesting that such cost savings compared to ground level were not sufficient to overcome the additional complexities and costs of elevated construction for HSR. *Hyperloop's* lighter weight may mitigate the cost of pylons. Moreover, obtaining clearances and other permissions will be a significant cost, particularly with a technology unfamiliar to agencies.

2.3.2.6 Missing cost components

A criticism of the *Hyperloop Alpha* proposal is that, in order to achieve ridership necessary to divert passengers from other modes and cover its capital costs, the route likely should continue into the urban core of both San Francisco and Los Angeles. At the northern end, the *Hyperloop Alpha* terminates in the East Bay but does not cross the San Francisco Bay into the city itself and the additional cost of bridging or tunneling under the Bay and into San Francisco would be substantial. As a point of comparison, New Jersey recently cancelled a similar two-track tunnel project under the Hudson River connecting New Jersey with New York City. The Access to the Region's Core tunnel project was budgeted at 8.7 billion USD, with some projections to 15 billion USD. A *Hyperloop* tunnel under the San Francisco Bay into the Transbay Center alone could exceed the proposed cost of the system.

At the southern end, expanding the route into Los Angeles Union Station would substantially increase the costs. Los Angeles is currently constructing a 2 mile rail tunnel connecting several rail

lines near downtown at a cost of 1.4 billion USD. Los Angeles Union Station is located 25 miles further south than Hyperloop's proposed endpoint. A project combining even some tunneling or raised guideway for 25 additional miles in an expensive urban environment would be substantial.

Also missing from the proposal is any capsule maintenance facility where they would be cleaned, maintained, and repaired. The description of the station describes a small platform capable of handling only three to four capsules at a time eliminating their capability to store capsules for service and inspection purposes. The cost of a maintenance facility would vary depending on the location and footprint of such a facility, however, using the estimated station cost as a proxy, each maintenance facility could cost around 125 million USD.

2.3.3 Effects of land on construction costs

Terrain topography (Figure 3) is one of the key components impacting Hyperloop infrastructure.

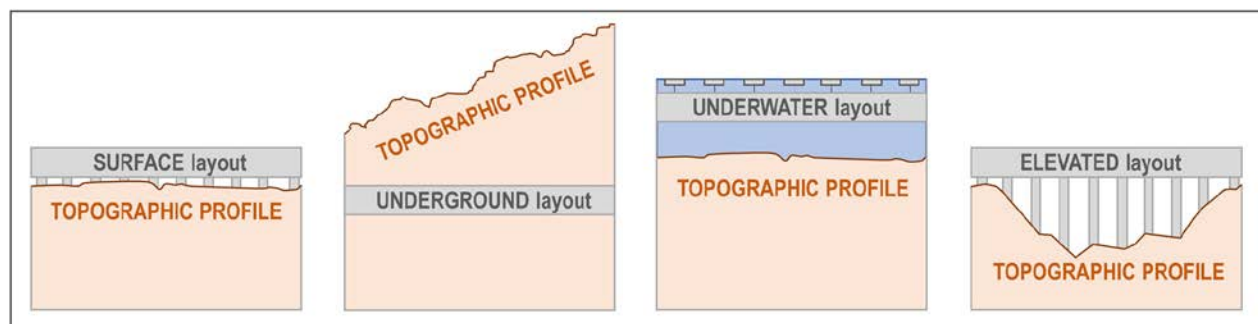


Figure 3. Layout typologies in a Hyperloop infrastructure. Source: (Gago, Perez Seoane, 2021)

As known from HSR projects, the costs of construction strongly depends on the geographical constraints. The graph in Figure 4 shows the average construction cost in relationship to the share of complex infrastructure like tunnels and bridges.

2.3.4 Operating expense analysis

An OPERating EXPense (OPEX) is an expense a business incurs in its normal business operations. It includes rent, equipment, inventory, marketing, payroll, insurance, step and funds allocated for research and development.

The *Hyperloop Alpha* proposal offers no discussion or projection of Operating & Maintenance (O&M) costs, apart from a single mention that its projected ridership and fare recovery covers daily operational costs with a 20 USD fare. Assuming that Hyperloop's largest operating cost, energy, is fully covered by the self-sufficient solar panel system, there are still daily O&M costs that must be considered. This section presents several key O&M cost areas that would need to be added to any comprehensive analysis of high speed transportation options. These costs are largely labor and dependent on the size of the Hyperloop operator's staff, but might be estimated by looking at overhead rates for similarly sized companies.

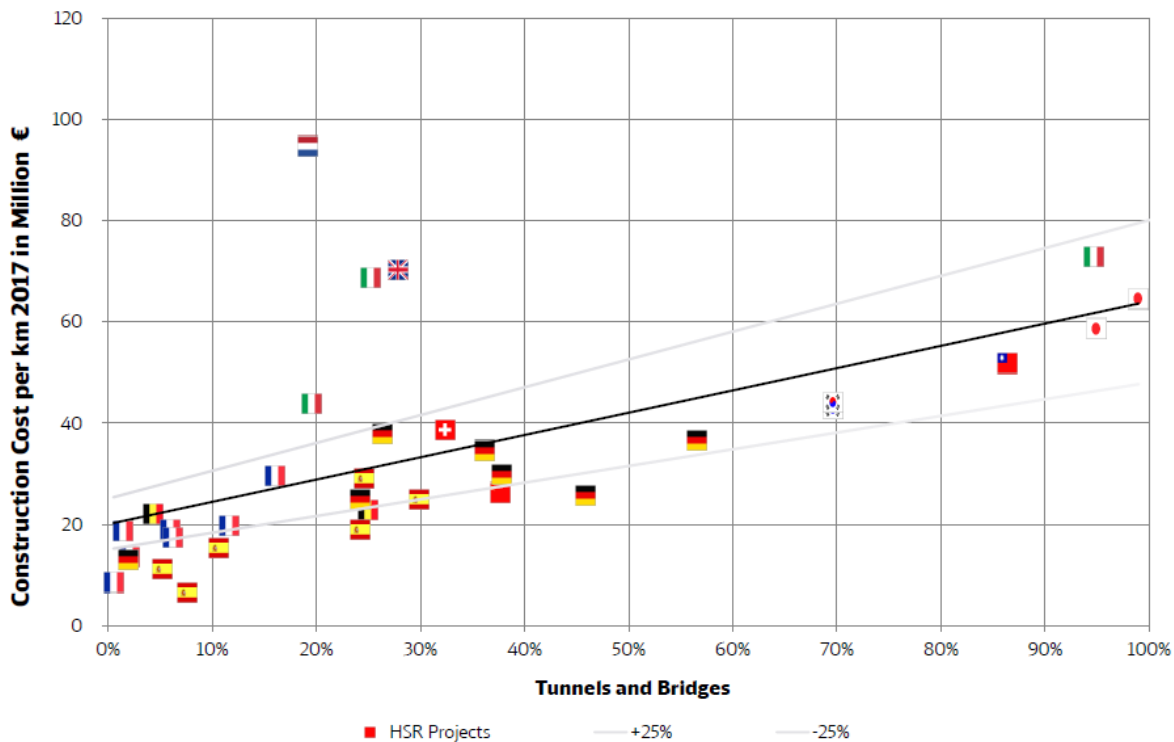


Figure 4. Average construction cost of tunnels and bridges. Source: Deutsche Bahn¹

2.3.4.1 Daily management, dispatching & system control

While the operation of the system itself is likely highly automated, some element of human control or supervision is needed from a central command center to address issues as they arise. Day to day system operation at a minimum includes dispatching, security and maintenance. If this work does not take place at one of the stations, the capital cost of a dispatch facility would need to be added to the cost estimate. An alternative to consider would be to decentralize traffic dispatching with vehicle-centric signalling systems (e.g. virtual coupling, moving block) potentially allowing at self-organisation of traffic by mutual negotiation procedures (SORTEDMOBILITY, 2021).

2.3.4.2 Management and planning

In addition to day to day system operation, general management is needed for strategic planning of the system, long term maintenance, personal management, IT services, and business development. If this work does not take place at one of the stations, the capital cost of a facility would need to be added to the cost estimate.

¹ Authorization of the use of the image is only valid for this research report. This graph is used on the report courtesy of Deutsche Bahn and it was made based on Deutsche Bahn's internal data. The graph is not publicly accessible.

2.3.4.3 Stations

The operating cost of stations was not mentioned in the proposal. While the *Hyperloop Alpha* proposal describes an electronic-only ticketing system that would eliminate ticket sales agents, station operations likely require other staffing. Examples of station labor costs for Hyperloop are safety and security personnel, customer service, vehicle maintenance or cleaning and customers' baggage assistance. Additional station costs will include utilities and water for restrooms, connections to other ground transportation and other customer amenities, such as coffee, Wi-Fi, bookstore, etc. These station operation costs need to be added to normal costs of operation.

2.3.4.4 Infrastructure inspection

Given the speeds involved and the narrow tolerances permitted, any Hyperloop technology must have a rigorous inspection regime to maintain safe operations. Amtrak inspects its high speed tracks visually twice a week and using an automated track geometry inspection vehicle roughly every 30 days. Amtrak's track geometry car inspects the rails as part of normal service as the car is coupled to a train ensuring that normal operations are not affected. Presumably an inspection vehicle will be created to inspect the interior of the tube at normal operating speed, but capital costs for an inspection vehicle need to be added to the cost estimate if not already integrated into each passenger vehicle. Federal regulators will likely require an exterior inspection of tubes and pylons be conducted at a much lower speed for periodic intervals. The cost for this inspection labor as well as any vehicles or equipment needed to inspect the tube (e.g. trucks, cherry picker lifts and electronic equipment for solar testing) need to be added to any cost estimate.

2.3.4.5 Infrastructure maintenance

No maintenance costs were mentioned in the *Hyperloop Alpha* proposal, but components will inevitably fail and need repair. These costs will need to be added to any cost estimate. Repairs within a tube will necessarily halt operations in that tube and depending on system redundancy may impact other tubes. Another large cost for any inspection and maintenance activity is the foregone revenue from any downtime if operations have to be halted. The redundancy of the system may impact its ability to continue revenue operations during a maintenance period.

2.3.5 Optimization tools

Due to the complexity of the costs structure and many trade-offs in the design, some companies has focused on developing optimizations tools (HOPS) (Kirschen P., Burner E., 2021). As Hyperloop presents optimization problem due to the often-competing objectives of minimizing CAPITAL EXpenses (CAPEX), OPEX, travel time within the many recursive design relationships inherent to the system architecture. Combining this with the fact it is a clean-sheet design problem makes Hyperloop a unique opportunity to impactful rigorous application of Multidisciplinary Design Optimization (MDO) techniques. A system optimization tool (HOPS are is capable of providing a fast and disciplined way of solving such an optimization problem by formulating it as a sequence

of geometric programs that can be solved using commercially available software. HOPS minimizes total cost per passenger-km and models everything from the diameter of the tube down to the current in the motor coils.

The general parameters can be observed in Figure 5.

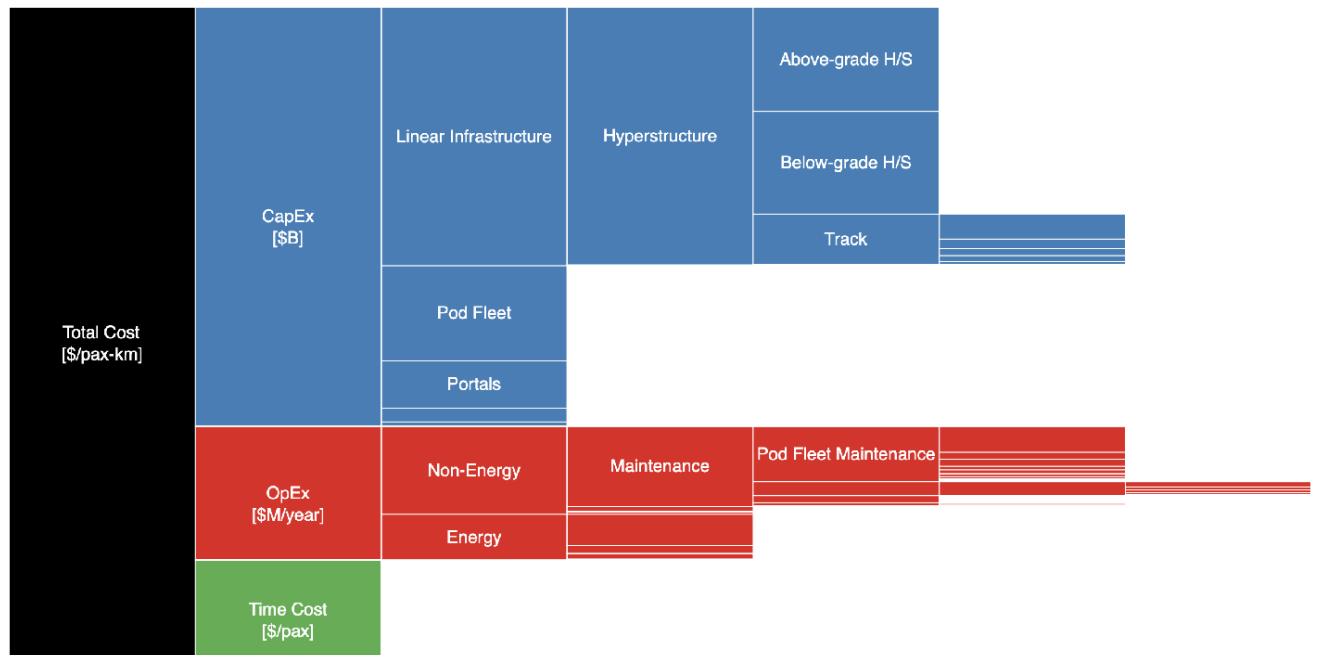


Figure 5. Breakdown of total cost. Source: (Kirschen P., Burner E., 2021)

2.3.6 Hyperloop construction costs in different countries

Since the first white paper covering Los Angeles to San Francisco route, many other studies have been conducted. One of such studies, which displays the performances of Hyperloop transport system (Van Goeverden K., Milakis D., Janic M., Konings R., 2017), compares Hyperloop with other transport modes as in Figure 6.

	Unit	HL	APT	HSR
Considered distance	Km	600	600	600
Operational performance				
Capacity	Seats/veh	28	130	1000
	Veh/h	10	3	12
	Pax/h	280	390	12000
Technical productivity ¹⁾	Seat-km/h ²	341600	323710	4200000
Quality of service ²⁾				
– travel time	Min	40,3	98,5	138,9
– frequency	Dep/h	10	3	12
– interconnectivity		+	++	++
– reliability		+++	+	++
Financial performance				
Costs				
– Line infrastructure	k€/year/km double track	825-2300	600	883,4
– Access points	k€/year/access point	4000	-	-
– Vehicles	k€/year/seat	29	48,8-65,4 ³⁾	2-4,7 ³⁾
	€/seat-km	0,008	0,033-0,035 ⁴⁾	0,031 ⁴⁾
Revenues/fares (€/p-km)	€/p-km	> 0,35	0,183	0,174
Social and environmental performance				
Energy consumption ⁵⁾	kWh/p-km	< 177	591	177
GHG (CO ₂) emissions ⁶⁾	g./p-km	0	120	40
Noise ⁷⁾		+++	++	+
Safety ⁸⁾		+++	+++	+++
Land use ⁹⁾	ha/km (net)	0,4	15	3,2-3,5
	ha/km (gross)	1,0	-	3,2

+: low performance; ++: moderate performance; +++: high performance

Figure 6. Comparing Hyperloop (HL) with HSR and Air Plane Transport (APT) counterparts.
Source: (Van Goeverden, Milakis, Janic, Konings, 2017)

2.3.6.1 Switzerland

The estimated costs of Hyperloop infrastructure was also considered for different local variants. The breakdown of costs for construction in Switzerland (Shah, 2019) is as in Figures 7 and 8.

No	Elements	Costs (Million CHF)					
		Hyperloop Alpha	van Goeverden et al.	Hardt	Transpod	Delft Hyperloop	Current Research
1.	Elevated Corridor (per km)						
	Foundation (Pylons)	8.23	53.73 ¹⁰	4.15	9.39	0.36	9.39
	Tube	2.10		8.83	13.35	22.99	13.35
2.	Underground Cost (per km)						
	Tunnel Cost	45.19	125.36 ¹⁰	4.87	-	63.41	63.41
3.	Station Cost (per nos.)				-	1261.77	239.53
	Vacuum Pumps (per km)	239.53	207.75	7.21 ¹¹	0.17	0.29	0.17
4.	Solar Panels (per km)	0.69	-	0.39	2.79	1.45	2.79
5.	Propulsion System (per km)	0.36	-	6.49	0.47	23.25	0.47
6.	Vehicles (per seat)	0.09	0.30	0.09	-	0.30	0.09

Figure 7. Comparison of the cost provided by different stakeholders converted to CHF (considering implementation in Switzerland). Source: (Shah, 2019)

No.	Element	Life Span (Years)	Average Annual Cost (CHF)	Maintenance Cost (CHF)
Maintenance Cost				
1.	Tube	75	530,600	53,060
2.	Tunnel	50	400,500	40,050
3.	Station (per nos)	50	7,185,900	718,590
4.	Propulsion	20	28,200	2,820
5.	Vacuum Pump	20	10,200	1,020
6.	Vehicle (per seat)	20	5,400	540
Operational Cost				
6.	Staff Cost	Station		14,779,900
		Vehicle		3,695,000
7.	Energy Cost (per 100 seat-km)			1.15

Figure 8. Maintenance and operational cost estimated for the case of implementation in Switzerland. Source: (Shah, 2019)

2.3.6.2 Italy

One study has explored the possibility of success of Hyperloop technology on Italian routes (Maja R., Favari E., Mariani C., 2020). Specifically, for the route Milan-Rome, which has been explored in the study, the following assumptions (Figure 9) have been made.

Track length	530	km
Tunnel length	111,3	km
Switch length	6	km
Number of capsules	27	/
Number of stations	2	/

Figure 9. Features of the Milan-Rome route. Source: (Maja R., Favari E., Mariani C., 2020)

Considering the cost parameters outlined above, the construction costs of Hyperloop for the Milan-Rome route result as in Figure 10.

Cost of open air infrastructure per km	24.617.199,00 €
Additional tunnel cost per km	25.430.000€
Switch cost per km	10.177.395 €
Expropriation cost per km	5.530.000 €
Station cost	700.000.000 €
Capsule cost	6.666.667 €
Total	20.449.438.849 €
Certification cost	1%
Cost Rome-Milan	20.653.933.238 €
Average cost per km	38.969.685 €

Figure 10. Construction costs of the Hyperloop for the Milan-Rome route. Source: (Maja R., Favari E., Mariani C., 2020)

2.4 Roadmap of transport innovations

In this chapter a generic overview is given of the transport sector evolution and existing innovations. Current trends towards the decarbonisation of transport sector and related novelties. Additionally, the necessary innovation for enabling the Hyperloop deployment, as well as the implementation roadmap of hyperloop innovations in short and long term are described with the necessary actions.

2.4.1 Transport evolution and existing innovations

Fast travel is seen as essential means for humans to access new grounds, connect with other people and gain new experiences. At the same time fast travel is used as a competitive advantage tool to show the advancement of the technology among manufacturers and operators (UIC, 2018). Fast travel and transport has been the main drivers for transport sector evolution starting with the horse carriage (Bleijenberg, 2017b).

Mechanization of the production enabled by the invention of the water and steam power engine led to what is generally known as the first industrial evolution. This allowed for the introduction of the steam locomotive in railways and steam-powered ships in maritime. Transport sector has been evolving continuously ever since then (Figure 11). The need for faster transportation and travels has been the driver for countless transport technology related inventions (Bleijenberg 2017b). In particular the innovations in the area of engine technologies have brought major transformation in the sector. The Internal Combustion Engine (ICE) innovation is considered as one of the major achievements in the human history. An engine powered by fuel led to faster railways, introduction of a range of vehicles on the road transport, larger ships in the maritime sector and the first air transport commercial services in 1920. This technology is still one of the most widely used in the transport sector, especially in the road transport industry.

The desire for enabling faster travel in railways led to the introduction of HSR (Annex A). Significantly faster than the conventional rail, the HSR is powered by electricity and is designed for speeds above 250 km/h for the high-speed lines and for speeds up to 200 km/h in the upgraded lines. Rolling stock is designed such that its aerodynamics profile can handle the air resistance which increases with the square of speed. In addition, full compatibility between the infrastructure and rolling stock enables high-speed performance and safe operations. The commercial deployment in 1964 of the Japanese Shinkansen marked the start of HSR transport services. Today the length of the high-speed lines has increased dramatically, with the majority of them located in China.

When compared to HSR, the travel time advantage of aviation increases with the trip distance. Since the average travel time budget per person remains constant, the higher speed translates into longer travel distances (Bleijenberg 2017a). Maximizing the distance with the given travel time budget provides mobility freedom and subsequently mobility growth, thus speed matters (Ausubel, Marchetti, Meyer, 2000).

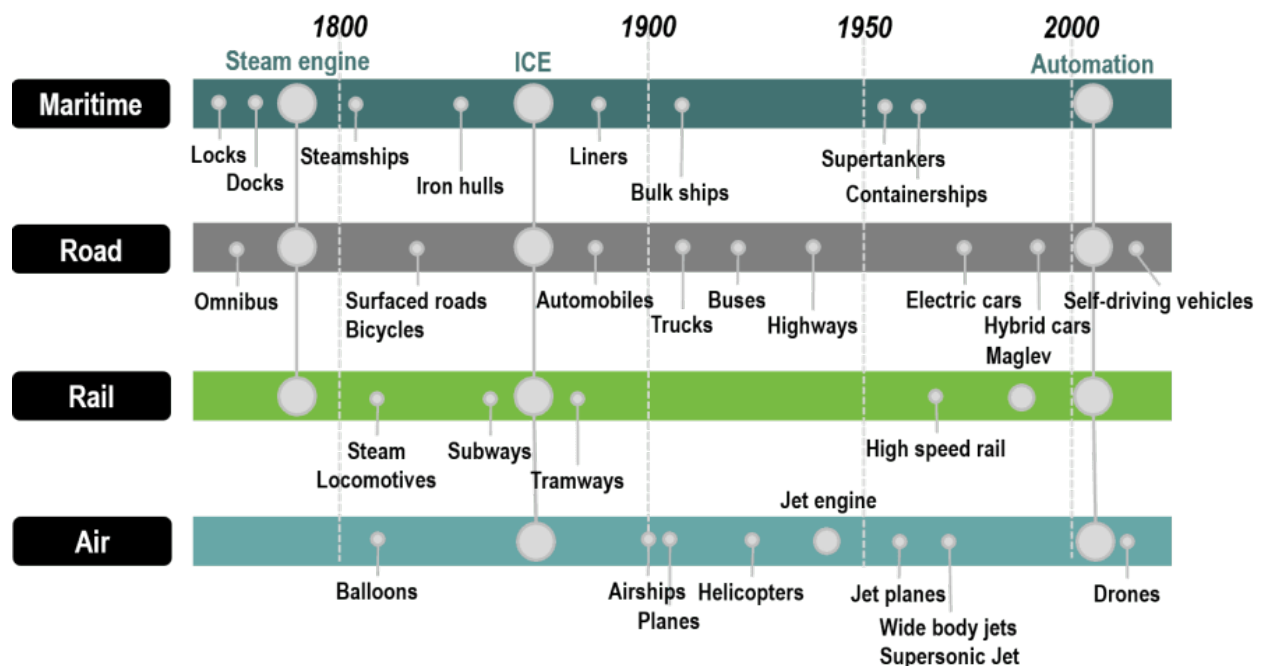


Figure 11. Transport evolution. Source:
<https://transportgeography.org/contents/conclusion/future-transportation-systems/evolution-transport-technology/>²

² Authorization of the use of the image is only valid for this research report. Conditions for use in any other reports

Length of the high-speed network in commercial operation worldwide (1964-2020)

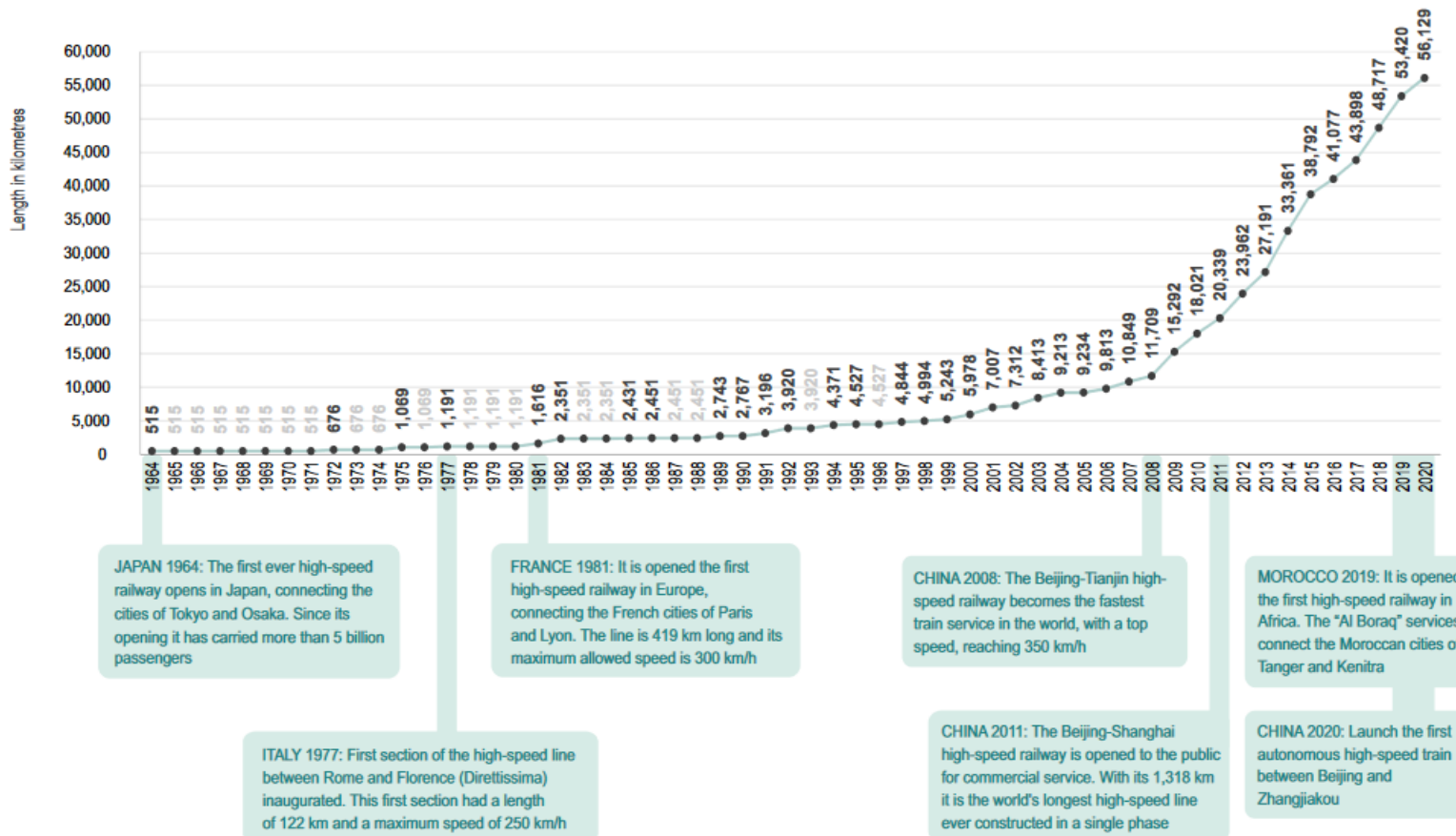


Figure 12. HSR commercial operations. Source: <https://uic.org/IMG/pdf/uic-atlas-high-speed-2021.pdf>

Shorter travel time is one of the main factors for determining the market share between rail and aerospace market. For example, travel time was found to be one of the determining factors for the choice of transport modalities in a recent study on replacing passenger flights from Schiphol within 700 km by HSR (Royal Schiphol Group, 2020). A flight from Schiphol to Berlin takes about one hour, whereas travelling by HSR takes more than 6 hours. Goal is to reduce this with 30 minutes, which still leaves HSR lacking behind in terms of travel time. High speed rail thus cannot really match aviation travel times.

Another existing technology achieving higher speeds than the HSR and closer to aviation is the already introduced Maglev, which uses the superconducting magnets generating magnetic fields for propulsion and suspension of the vehicle, without mechanical contact between train and guideway. Nevertheless even though commercially available since 2002 in Shanghai, due to its high initial development costs and despite its likely advantages compared to HSR, it is not widely deployed. Some of the factors impacting the development costs have been mentioned in (Bird, 2019). This is due to the specialized elevated guideway that needs to be constructed in order to accommodate the suspension technology of the vehicle, a linear synchronous motor for propulsion along the guideway and the complex switching mechanism.

The expectation is that reducing travel times will remain relevant for future transport. In addition for future resilient transportation requires an infrastructure affordable to build and maintain, energy efficient with zero emissions, easy to integrate into the environment, offering a high capacity and being competitive in speed with the existing modes. Hyperloop could represent such future-proof transportation system for passengers and cargo. It outperforms aviation, rail and road, in costs, energy efficiency and easiness of spatial integration, transport capacity and times for a large range of distances. The World Economic Forum [World Economic Forum, 2020] has identified the hyperloop-based services as one of the 20 new markets that can drive tomorrow's economic transformation.

2.4.2 Sustainability and decarbonisation of transport

According to United Nations Economic Commission for Europe (UNECE), current transport modes are responsible for 30% (Figures 13 and 14) of all greenhouse gases in the developed world and 23% worldwide. At the same time, according to the International Transport Forum (ITF) of the Organization for Economic Co-operation and Development (OECD), the expectation is that the transport sector will grow. Facilitating this growth in a sustainable manner imposes an innovation challenge that can only be solved through innovation in existing modes as well as introduction of new transport modes.

According to the International Energy Agency (IEA), 74.5% of the transport emissions comes from road vehicles, where cars and buses contribute for 45.1% and the residual 29.4% originates from freight transport (Ritchie, 2020).

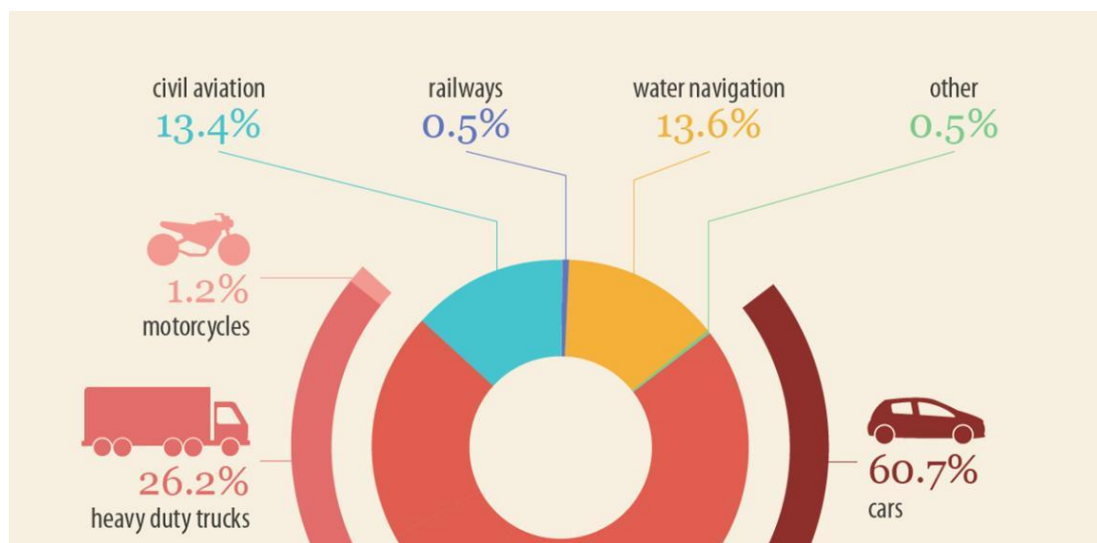
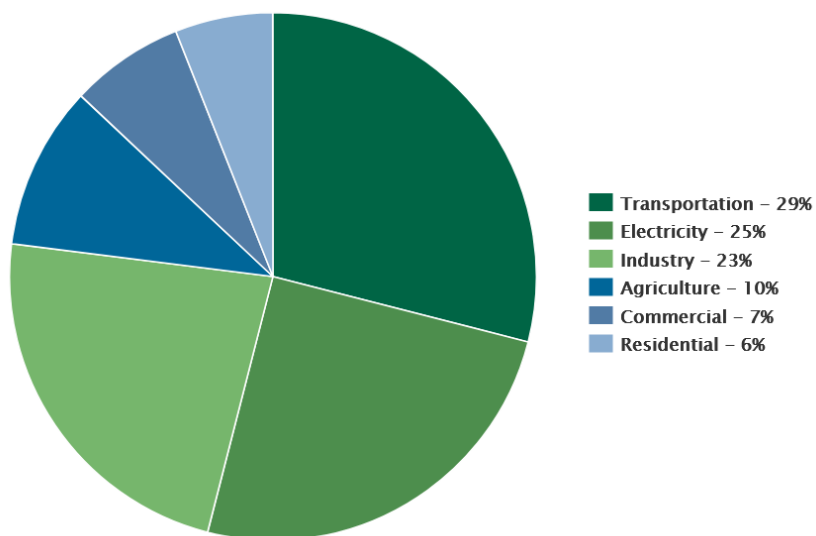


Figure 13. CO2 emissions breakdown in 2016 in Europe. Source:
<https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics>



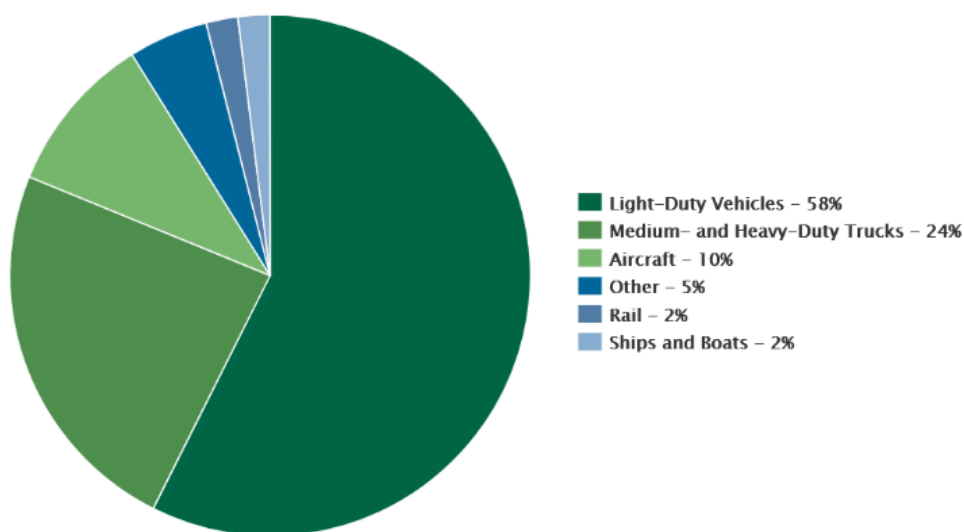
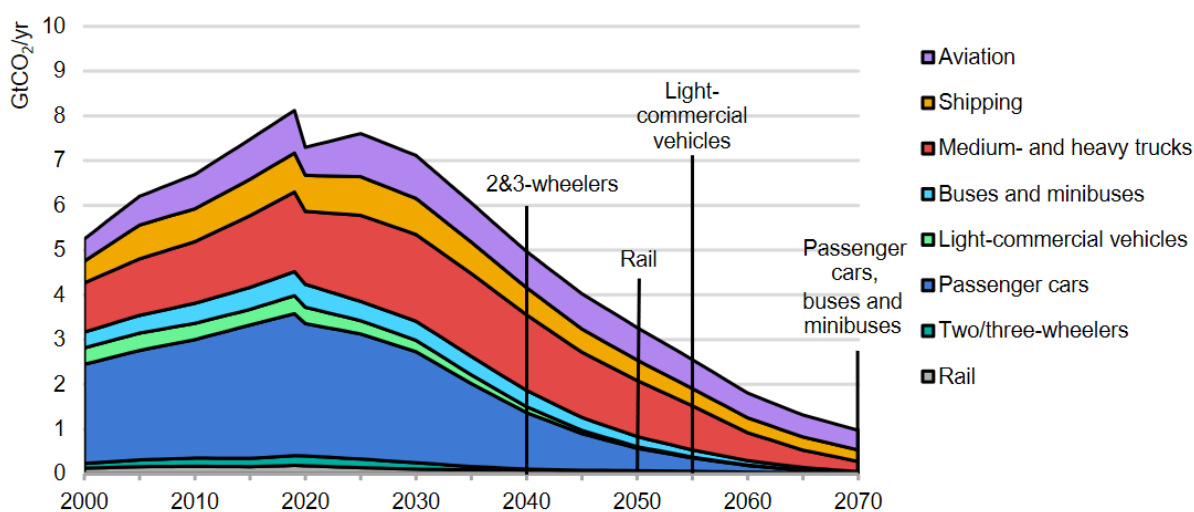


Figure 14. U.S. greenhouse gas (GHG) emissions 1990–2019. Source:
<https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions/>

Two-thirds of the emission reductions needed must come from technologies that are not yet available. In particular, emissions from long-distance road transport and aviation are difficult to eliminate and in 2019 they accounted for 2 Gt CO₂ (Faber J., Lee D.S., 2020).

Looking into the future projections, most modes of transport are expected to be emission free (Figure 5). However, trucking, shipping and aviation still continue to produce some emissions due to practical difficulties with their decarbonisation. For example, heavy-duty trucking would require infrastructure for fast charging and larger hydrogen refueling stations.



IEA 2020. All rights reserved.

Figure 15. Global CO₂ emissions in transport by mode in the Sustainable Development scenario, period 2000-2070. Source: IEA 2020

In the efforts to enable decarbonisation, the European Commission adopted a package of proposals to make the EU's climate, energy, land use, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels to be integrated the proposals for an *EU Climate Law*. This comes in addition to the sustainable and smart mobility strategy actions that lays the foundation for how the EU transport system can achieve its green and digital transformation and resiliency to future crises. As outlined in the European Green Deal, the result will be a 90% cut in emissions by 2050, delivered by a smart, competitive, safe, accessible and affordable transport system. The main milestones are depicted in Figure 16.

The major components in decarbonisation of transport, as well as the related instruments, have been identified by (United Nations Environment Programme, 2019) (Table 1). There are four major components:

- Reduced energy for transport;
- Electrification of transport;
- Fossil fuel substitution with biomass energy and hydrogen;
- Modal shift to other transfer modes.

2.4.2.1 Innovations on energy alternatives and optimizations

Many advances on on-board energy supply have been developed recently. This has allowed the appearance of some innovative trains that can use on-board energy systems to thrust themselves, without catenary, such as hydrogen or battery-powered trains. These innovations have proved that on-board hydrogen or battery supply can be safe and reliable for mass passenger transport.

2.4.2.2 Hydrogen trains

Europe is looking at options to replace its diesel-powered train fleet against the backdrop of climate change and the need for fast and consistent decarbonisation of the entire energy and transport system. Fuel Cell and Hydrogen (FCH) trains provides a flexible, zero-emission and potentially cost-competitive solution to replace diesel trains. In fact, by 2030, 1/5 of newly purchased trains in Europe could be powered by hydrogen. The latest developments in the field in Germany and France show that this technology will complement electrification in Europe and enable the complete decarbonisation transformation in rail with the flexibility it offers to the train operators (Roland Berger, 2019).

Fuel Cell and Hydrogen (FCH) trains hold the promise of fulfilling the operational requirements of rail transport, especially where track electrification is not economically feasible.



Figure 16. EU milestones towards sustainable mobility. Source: EU COM/2020/789

Table 1. Decarbonisation of transport components, instruments, co-benefits and potential reductions (Source: United Nations Environment Programme, 2019)

Decarbonisation of transport			
Major Components	Instruments	Co-benefits	Annual GHG emissions reduction potential of renewables, electrification, energy efficiency and other measures by 2050
Reduce energy for transport Electrify transport Fuel substitution (bioenergy, hydrogen) Modal shift	Pathways for non motorized transport Standards for vehicle emissions Establishing of charging stations Eliminating fossil-fuel subsidies Investment in transport	Public health from more physical activity and less air pollution Energy security Reduced fuel spending Less congestion	Electrification of transport 6.1 GtCO ₂

In contrast to competing clean technologies like batteries, FCH technology can provide higher flexibility for operators due to the long range and high-power ratings. FCH trains highlights can be summarized in the following points:

- Make economic sense above all when they are used on longer non-electrified routes of over 100 km;
- Can be used especially for last mile delivery routes, but also for main routes that have very low utilisation (about 10 trains/day);
- Enable operation with very short downtimes of less than 20 min (thanks to fast refuelling) and are able to withstand long operating hours of more than 18 hours without refuelling.

The use of FCH technology seems to be especially economical for a dense, non-electrified network with average utilisation by trains that also reach out to more rural or mountainous areas. The FCH technology can also offer advantages for cross-border operation as it can be operated independent of catenary voltage level, which differs across many countries. FCH trains become interesting as a feasible zero-emission solution where service frequency does not justify high catenary electrification investment.

FCH trains are an economically feasible clean alternative to current diesel trains in many cases. However, although the regional fuel cell train is already an attractive alternative today, room for cost cuts also exist to further improve competitiveness for other types of use cases. Cost reductions will likely come from the fuel cell system, on-board hydrogen tanks and the value chain for hydrogen fuel, with the largest reductions available from the cost of fuel. Today the fuel cell system accounts only for about 3-5% of the train total cost of ownership, equivalent to 10-15% of purchasing cost. Similarly, the hydrogen tank accounts for roughly 3-5% of the total cost of ownership. With projected cost improvements, the combined cost share of the fuel cell system and tanks should fall to approximately 2-4%: a decline of about 60%. When it comes to the fuel, today it probably accounts for about 40-50% of a train's total cost of ownership and could decline to around 20-30% in 2030.

Ongoing projects already exist, and stakeholders have announced several more: there are already trains operating in Germany, and the East Japan Railway Company has announced it will develop hydrogen fuel cell trains with expected delivery in 2024.

In 2016 Alstom presented for the first time its FCH train, the Coradia iLint. Two years later, in 2018, the iLint started the commercial service in Germany, running at a top speed up to 140 km/h without any local emission. Alstom is expected to deliver to Germany a further 14 set of trains by 2021, when a stationary filling station will start operating. Moreover, Coradia iLint have been also operating in Austria since 2020 in a regular passenger service. Also, French operator SNCF ordered 12 of them for 2021.

Spanish company Talgo is also developing a hydrogen-powered regional train called Vittal-One. Its expected entry into services will be by 2023, with its validation being carried out in 2021. In a joint project, Deutsche Bahn and Siemens Mobility are testing a brand-new complete system consisting of a newly developed train and a newly designed filling station. Siemens Mobility is developing the next generation of hydrogen trains that are based on the proven, high-performance Mireo commuter train, which is also used in battery-powered operation. Equipped with a fuel cell drive

and a lithium-ion battery, it provides local, emission-free mobility on non-electrified routes. It will be trialed in 2024 with view to replace diesel engines on German local rail networks.

2.4.2.3 Battery trains

A Battery Electric Multiple Unit (BEMU), also called battery electric train, is a recent innovation in guided transport means. It consists of a train, whose energy is derived from rechargeable batteries in charge of driving the motors. Therefore, it needs no electric ground rail or catenary. It is an interesting option to decarbonize the rail industry without incurring major investments on building and maintaining catenaries.

Lately, these solutions have become increasingly popular in tramways. By using a combination of Li-ion batteries and super-capacitors that are charged while braking or waiting at the station, trams can operate without catenary. This becomes very interesting for cities that want to reduce the infrastructure costs and the visual impact of public transport. However, the potential of battery-powered mobility is not limited to smaller vehicles like trams, real-world applications are already showing that battery power is also a practical alternative to larger diesel-operated commuter service.

Various forms of battery-powered mobility have been around for nearly a century, but until recently, battery-powered mobility has been limited by the massive size and number of batteries required to move large vehicles. Any battery strong enough to move a heavy vehicle like a train would be too large for the train to carry. Yet recent advances in lithium-ion fuel cell technology have turned the corner and taken the idea of battery-powered mobility off the drawing table and put it onto the tracks.

Batteries evolution over the last 20 years has allowed the implementation of this technology today in regional trains as well. As an example of this Bombardier offers a portfolio of commuter trains, which can run on battery power enabling catenary free operation up to 100 km. Bombardier trains feature a propulsion and energy management system called MITRA, which consists of a high-efficient converter and an on-board set of batteries and super-capacitors. Also, UK-based firm Vivarail has developed a BEMU with a range of 160 km and a recharging time of only 10 minutes. It is an operational train, which has already reliably run thousands of miles in testing.

Other train manufacturer companies, such as Alstom, Siemens and Hitachi Rail are currently developing their own models of battery electric trains, as the technology looks very promising.

Currently, battery electric trains are heavy and can only travel relatively short distances, however, with the expected evolutions of batteries over the next five to ten years, BEMUs will likely become lighter and able to travel further distances.

In some cases, battery-powered trains may appear as a more cost-effective option than FCH or Diesel trains, but come with operational constraints resulting from their highly route-specific tailored battery configurations.

BEMU are, therefore, more suitable for *bridging* non-electrified routes between electrified lines, or making a return run on a branch line linked to an electrified main line. BEMU fitted with propulsion batteries will of course incur a higher initial purchase price and, depending on the specific operational requirements, may also require considerable additional infrastructure to be installed to facilitate propulsion battery recharging. The limitations on maximum achievable range means that a wholly battery powered EMU is not yet a completely viable alternative to Diesel on all non-electrified routes. However, electric trains are generally more reliable than their diesel counterparts, require less maintenance, are quieter and produce far less direct CO₂ and pollution.

2.4.2.4 Energy storage systems

Although it is true batteries cannot deliver the energy required considering today's technology, academics and institutions foresee that, by 2030, the energy density of batteries will have increased. As shown in Figure 17, forecasts predict that battery gravimetric density will probably double today's values.

Alternatively, hydrogen can also be used for energy storage purposes. Hydrogen technology is very promising and currently there is a strong support for developing this technology by the European Union and its member states (Roland Berger, Inycom, 2021). Hydrogen as an energy storage system combined with fuel cells has been already used in trains or cars. Research is also being driven to implement this technology in aircraft, whose smaller versions are expected to enter into service by 2024, while narrow body models will become a reality by 2030. Figure 18 shows the European hydrogen roadmap for transport applications.

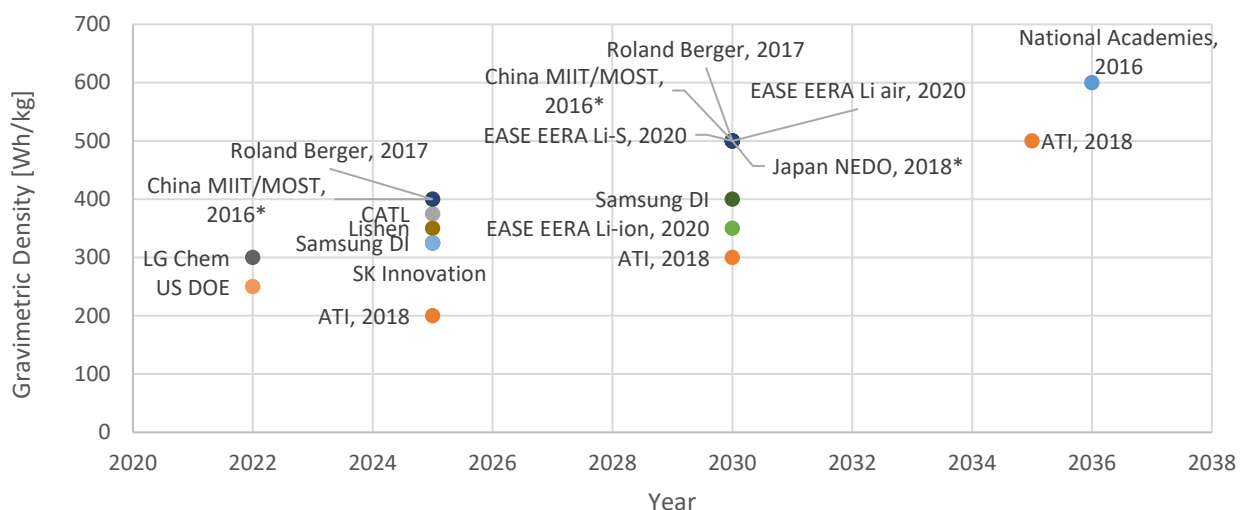


Figure 17. Battery energy gravimetric density forecasts.

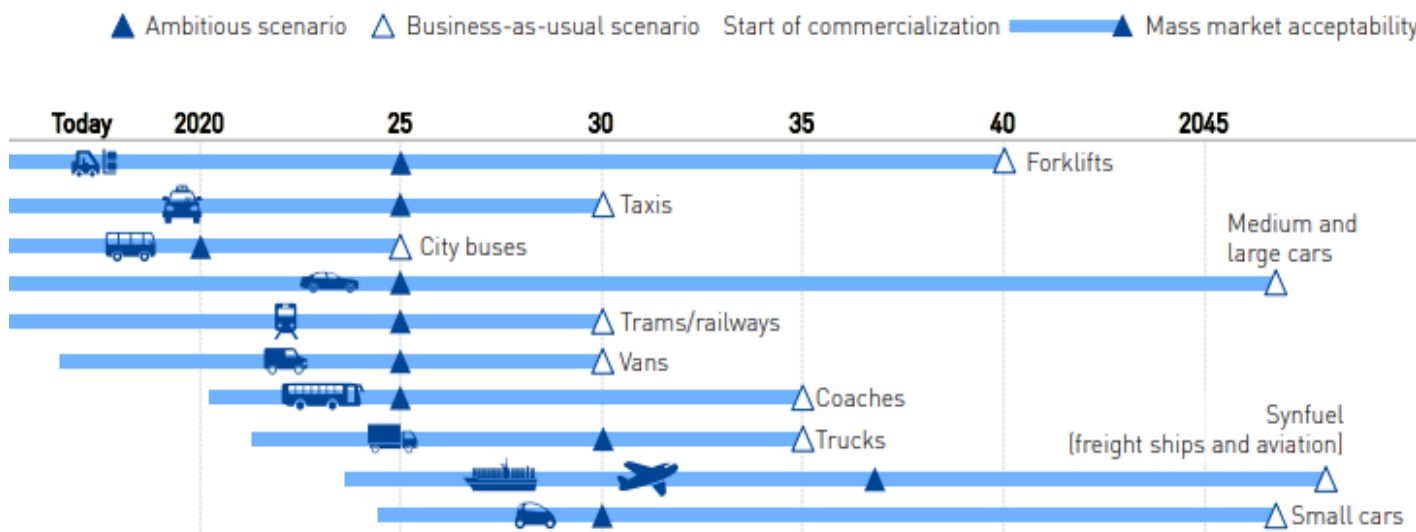


Figure 18. European hydrogen roadmap by means of transport. Source: FCH Joint Undertaking, 2019

Extensive research is being carried out (1) lightening hydrogen storage tanks safely, (2) increasing fuel cell power density, (3) speeding up refuelling times and (4) producing green hydrogen efficiently (FCH Joint Undertaking, 2019).

2.4.2.5 Vehicle innovations

In the Railway sector, at Shift2Rail Multi-Annual Action Plan, some planned railway innovations are described together with their respective roadmap. As explained above, the work conducted within the Shift2Rail framework is structured around five asset-specific Innovation Programmes.

Within the Innovation Program 1 on *Cost-efficient and reliable trains*, Shift2Rail focuses on rolling stock as one of the key elements. In this framework, the most relevant innovations that could help improve the Hyperloop vehicle, are the use of composite material technologies, in car bodies (TD1.3), doors (TD1.6) and running gears (TD 1.4). Using composites vehicles can achieve a weight reduction of 15-30%, possibly resulting into an operational energy savings of 2-12% (Figure 19).

In the Aviation sector, Clean Sky 2 is a joint undertaking between the European Commission and the European aeronautics industry that develops innovative technologies for greener aviation, aiming to reduce CO₂ emissions and noise levels. Clean Sky 2 is the protagonist of Europe's aeronautical research and innovation, championing the air transport needs of tomorrow's increased mobility.

In Clean Sky 2 Joint Undertaking Development Plan, the demonstration projects are described together with their roadmap for achieving high TRL. Some of those demonstration areas could be implemented in a Hyperloop vehicle, to improve its features.

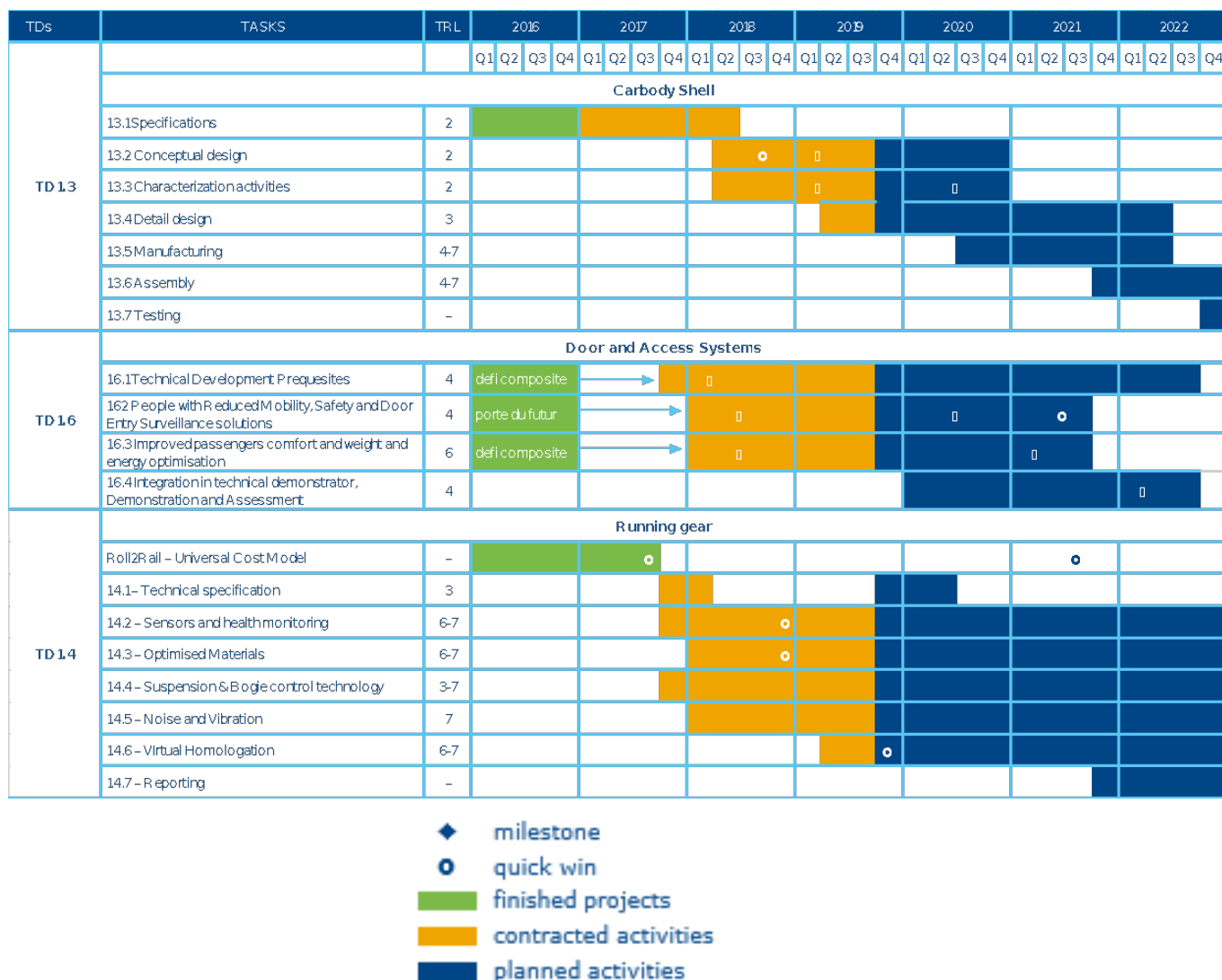


Figure 19. Shift2Rail roadmap for vehicle innovations. Source: Shift2Rail, 2019

Within the theme of *Innovative structural/functional design and Production systems*, specifically in the demonstration area of *Cabin and Fuselage*, some demonstrators appear to be interesting for a Hyperloop vehicle (Figure 20).

Moreover, in the *Next Generation Cockpit Systems and Aircraft Operations* theme, two interesting demonstration areas exist as well. For the theme Aircraft Non-Propulsive Energy and Control Systems, the demonstration areas: Electrical systems, Landing systems, and Non-propulsive Energy Optimization become relevant for Hyperloop vehicle optimization (Figure 21).

Finally, under the theme *Optimal Cabin and Passenger Environment*, two interesting demonstration areas arise: Passenger Comfort and Innovative Cabin Passenger/Payload systems. These areas contain a number of relevant demonstrators (Figure 22) that could be applied in the Hyperloop cabin.

2.4.2.6 Modal shift

The modal shift towards the public transportation as well as other non-motorized means of transport is normally seen as long term strategy that will aid in decarbonisation of the transport sector. Nevertheless, the global climate change crisis requires an urgent acceleration. In this context, the modal shift towards more sustainable transport modes, such as, increasing the number of passengers travelling by public transport as well as shifting a substantial amount of goods onto rail, inland waterways and short sea shipping is one of the pillars for actions defined by the European Commission strategy for sustainable and smart mobility (European Commission, 2020).

State of play as of November 2020					◆ CD ◆ PDR ▲Testing/GT ◆CoR ET = Enabling Technology									
Demonstrator /Technology Streams Maturing Over Time														
Theme	Demonstration Area	Demonstrator /Technology Streams	Number of ETs	TRL at End	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Innovative Structural / Functional Design - and Production System	Cabin & Fuselage	REG D3 - Full scale innovative Fuselage & passengers Cabin demonstrator (Structural demonstration)	3	6					◆	◆		▲		
				TRL Maturity		TRL3		TRL4	TRL5		TRL6			
		AIR-D3-24 Cabin Parts for SAT structure [WP B-3.4]	1	6		◆		◆		▲				
				TRL Maturity				TRL3		TRL4	TRL5	TRL6		
		AIR-D1-1 Metallic Cargo Door [WP-A-3.3]	1	6		◆		◆		▲				
				TRL Maturity			TRL3		TRL4		TRL5	TRL6		
		LPA-02-D1: Next Generation Fuselage, Cabin and Systems Integration	8	5					◆	◆		▲▲	▲	▲
				TRL Maturity						TRL2		TRL3	TRL4	TRL5
		AIR-D1-16 & D3-26 - Regional	4	6		◆		◆			▲			
				TRL					TRL3		TRL4	TRL5	TRL6	

State of play as of November 2020					◆ CD ◆ PDR ▲Testing/GT ◆CoR ET = Enabling Technology									
Demonstrator /Technology Streams Maturing Over Time														
Theme	Demonstration Area	Demonstrator /Technology Streams	Number of ETs	TRL at End	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
		Aircraft Fuselage and Cabin Major Components Demonstrator [WP B-4.3, B-4.4]	8	Maturit y										
		LPA-02-D3: Next Generation Lower Center Fuselage		2		◆			◆					
		TRL Maturit y								TRL2				
Next Generat ion Cockpit Systems and Aircraft Operati ons	Cockpit & Avionics	D25 Integrated modular communications	1	5					◆					
				TRL Maturit y					TRL3			TRL4		
	Advanced MRO	LPA-03-D4: Maintenance service operations enhancement demonstrator	14	4					◆	◆	▲			
				TRL Maturit y				TRL2		TRL3	TRL4			

Figure 20. CS2 Roadmap for cockpit and fuselage innovations. Source: Clean Sky 2, 2020

State of play as of November 2020					Demonstrator /Technology Streams Maturing Over Time									
Theme	Demonstration Area	Demonstrator /Technology Streams	Number of ETs	TRL at End	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Aircraft Non-Propulsive Energy and Control Systems	Electrical systems	D10. HVDC Power Management Centre for large A/C - Demonstration	2	5*										
				TRL Maturity					TRL3		TRL4			TRL5
		D16. Thermal Management demonstration	2	5										
				TRL Maturity								TRL4		TRL5
		D9. Innovative Electrical and control/Command Networks for distribution systems - Demonstration	3	4										
				TRL Maturity					TRL3					TRL4
		D19. Electrical power generation and distribution for SAT	2	5										
				TRL Maturity					TRL3		TRL4	TRL5		
		D13. Next Generation Cooling systems	1	6										
				TRL Maturity						TRL3		TRL4	TRL5 /6	
		D8. Innovative Power Generation and Conversion	4	5										
				TRL Maturity				TRL3		TRL4		TRL5		
	Landing	D17. Advanced Landing Gear	1	5										

State of play as of November 2020					Demonstrator /Technology Streams Maturing Over Time									
Theme	Demonstration Area	Demonstrator /Technology Streams	Number of ETs	TRL at End	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	Systems	Sensing & Monitoring System		TRL Maturity 5			TRL3		TRL4		TRL5			
		D5. Advanced Landing Gear Systems		TRL Maturity 6					TRL3	TRL4	TRL5			
		D6. Electrical Nose Landing Gear System	2	TRL Maturity 6										
				TRL Maturity 5			TRL3	TRL4	TRL5			TRL6		
	Non-Propulsive Energy Optimization	LPA-01-D15: Non-Propulsive Energy Optimization for Large Aircraft	4	TRL Maturity 5										
				TRL Maturity					TRL3			TRL4	TRL5	

Figure 21. CS2 Roadmap for energy and control systems innovations. Source: Clean Sky 2, 2020.

State of play as of November 2020					♦ CDR ▲ FT PDR Testing/GT ET = Enabling Technology Demonstrator /Technology Streams Maturing Over Time									
Theme	Demonstration Area	Demonstrator /Technology Streams	Number of ETs	TRL at End	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Optimal Cabin and	Passenger Comfort	D22. Comfortable & Safe Cabin for SAT	3	4					♦	♦				
				TRL					TRL3		TRL4	TRL5		

State of play as of November 2020					♦ CDR ▲ FT PDR Testing/GT ET = Enabling Technology Demonstrator /Technology Streams Maturing Over Time									
Theme	Demonstration Area	Demonstrator /Technology Streams	Number of ETs	TRL at End	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Passenger Environment				Maturity										
		REG D3 - Full scale innovative Fuselage & passengers Cabin demonstrator (Comfort/Thermal demonstrations)	1	6					♦		♦			
				TRL Maturity		TRL3				TRL4	TRL5		TRL6	
		SAT D3 - Safe and comfortable cabin	2	5									▲	
	Innovative Cabin Passenger/Payload systems			TRL Maturity							TRL4			TRL5
		AIR-D2-8/9/10/11 - Ergonomic flexible cabin [WP 5.1]	1	6						▲				
				TRL Maturity				TRL3		TRL4		TRL5		TRL6
		D2. Equipment and systems for Cabin & Cargo applications	1	5							♦	♦	▲	
				TRL Maturity						TRL3	TRL4		TRL5	
		LPA-02-D2: Next Generation Cabin & Cargo Functions	7	Up to 6								▲	▲▲	▲
				TRL Maturity						TRL3	TRL4	TRL4 /5	TRL5	TRL6

Figure 22. CS2 Roadmap for cabin innovations. Source: Clean Sky 2, 2020.

Railway sector is on its way towards reducing emissions for the 55% target for 2030 and net zero before 2050. In addition it is preparing for accommodating growing demands for both passenger and freight transport. Combined alternatives are also being studied as part of intermodality, mobility as service solutions as well as alternatives where there is a partial shift such as between aviation and rail and rail and road traffic. For example, intermodal freight transport between rail and road (Figure 23), has an important growth.

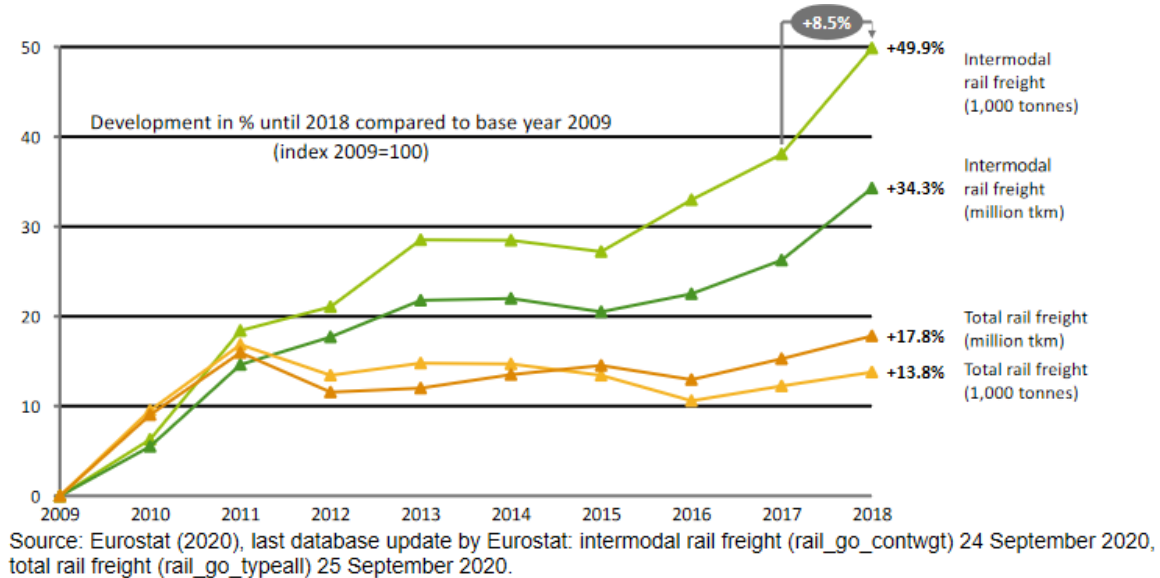


Figure 23. Development of total rail freight performance vs. rail transport of goods in intermodal transport units in Europe. Source: UIC Freight Department, 2020

The potential CO₂ reductions by a modal shift from aviation to railways may be 6-11% in intra-European aviation and 2-4% of CO₂ from all fuel bunkers in Europe, which includes departing intercontinental flights. The global transportation needs are expected to grow 2.5 times by 2050. Facilitating this growth in a sustainable way imposes an innovation challenge that can only be solved through innovation in existing modes as well as introduction of new transport modes.

Hyperloop is an excellent alternative for the modal shift from road, rail as well as aviation in order to meet the growing demand on one hand and environmental goals on the other hand. The analysis presented in (HARDT, 2020) show that Hyperloop would be able to substitute up to 12.5 million of the passengers that will travel through Schiphol airport by 2050 in distance ranges (100-500 km, 500-1750 km and 1750-3000 km) where hyperloop is beneficial and can substitute a share of high-speed rail and aviation routes.

According to the European Commission, 1,500 billion EUR needs to be invested in the comprehensive European transport infrastructure during the next decennium (European Commission, 2018). In selecting the projects for these investments, short-term congestion relief needs to be carefully weighed against the long-term sustainable opportunities that new solutions could bring, as the consequences of these investments last a lifetime.

2.4.3 Implementation roadmap of Hyperloop

The introduction of the Hyperloop concept aids in modernizing the transportation industry. The required Hyperloop innovations are identified in the HYPERNEX Deliverable 2.1. The necessary actions are identified based on the gaps for the short term as well as for the long term. Ensuring real scale high speed testing and thereafter scalability towards commercially viable hyperloop infrastructure through R&D public-private frameworks and at the same time suitable governance for enabling legislation/regulations are the first actions in the implementation roadmap of hyperloop innovations. Further in the long term challenges arising during the exploitation phase will lead to other research areas such as intermodality, spatial integration as well as research into other societal benefits and impacts.

Some studies have already defined possible roadmap for Hyperloop commercialization (Arup, BCI, TNO, VINU, 2017) (Deloitte, Antwerp Management School, VIL, HARDT, 2019). Possible timelines for the commercialization roadmap are depicted in Figure 24. As it can be seen in this study there have been four phases defined, based on the Technology Readiness Levels.

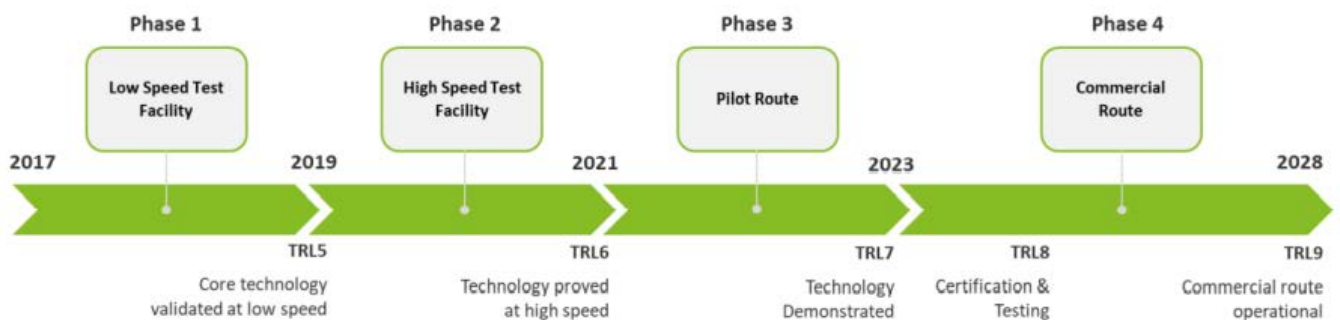


Figure 24. Commercialization roadmap of hyperloop innovations. Developed based on source: (Deloitte, Antwerp Management School, VIL, HARDT, 2019)

Based on (Arup, BCI, TNO, VINU, 2017) the implementation roadmap from short-term concept realization to market introduction can be decomposed into three phases (Figure 25):

- *Innovation phase*: the purpose is to demonstrate the concept at low and high speeds, proving Hyperloop is *innovation ready* to be implemented.
- *Realization phase*: the initial implementation serves to a first pilot route for cargo and passenger transportation, later transforming into a full commercial route; the initial implementation is not necessarily at the same location as the high-speed demonstration.
- *Exploitation phase*: the first commercial route is in operation.

During the *innovation phase*, the prototyping and testing facility is developed, in which essential Hyperloop technologies have been tested separately and integrated. Such facilities are already in operation. The next step in the innovation phases focuses on the development of high-speed test facilities, to prove the hyperloop can operate on promised high speeds. Several developments are ongoing, e.g. EHC in Groningen (NL), Certification Center in West Virginia (US) to build the high-speed test facilities. Besides the development of the high-speed test facilities, broader research

programs need to be setup among governments and industries to assess key topics and required innovations in short-term and long-term perspectives.



Figure 25. Implementation roadmap of hyperloop innovations. Source: (Arup, BCI, TNO, VINU, 2017)

In the *realization phase*, a short part of the route will first be used to combine the knowledge gained in a full-scale system. The short route can thereafter be extended into a commercial route.

The *exploitation phase* commences with the operational commercial route.

The progress along the phases requires extended short-term and long-term research actions (Figure 26). Each of the identified stages requires involvement of various stakeholders and the definition of stages and stakeholders' involvement will increase the success of realization.

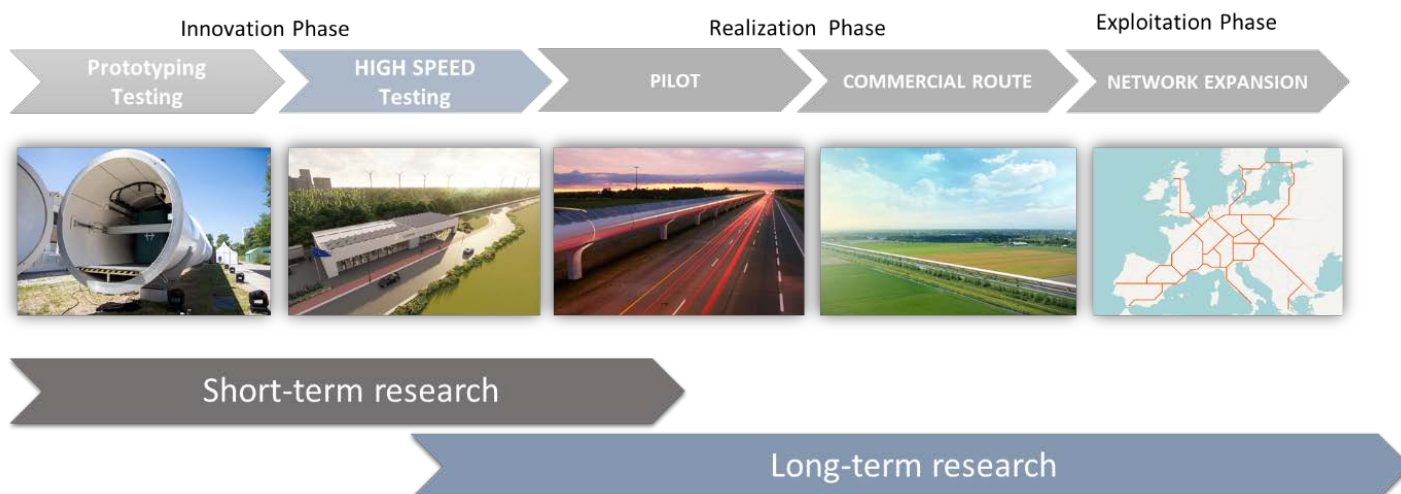


Figure 26. Mapping of short-term research/long term research to the implementation roadmap.

2.4.3.1 Stakeholder innovation strategies to Hyperloop

For a large infrastructure system as Hyperloop, as numerous stakeholders will have a direct influence on projects, these should be early involved in the process to accelerate the development or ensure they will not hinder the progress. Hence, the involvement of the right stakeholders is vital to the success of the system.

Building on the innovation strategies, in (Arup, BCI, TNO, VINU, 2017) four innovation strategies have been identified for Hyperloop development. This is based on the role (facilitating vs. leading) and the focus (technology vs. market) (Table 2).

Table 2 Innovation strategies of stakeholders

FACILITATING ROLE	Innovation Driver: The driver strategy suggests a leading role in technology development, i.e. by funding support for demonstration.	Front Runner: The active role to kick-start the commercialization of hyperloop, i.e. by investing in the project in the early phases.
LEADING ROLE	Innovation Catalyser: The approach that is marked by a facilitating role towards hyperloop technology development, i.e. in the form of removing regulatory barriers or providing in-kind support.	Market Shaper: The facilitating role to shape the environment necessary to commercialize a technology.
	FOCUS ON TECHNOLOGY	FOCUS ON MARKET

The study recommended the Dutch Government to take up the role of both Innovation Driver by setting up a R&D program and a test site to further progress the Hyperloop development, and Market Shaper by initiating a feasibility study for a first commercial track.

2.5 Standardization

2.5.1 Overview of standardization

Standardisation is the process by which standards are developed. They are documents made available to the public to be used, on a voluntary basis, and prepared by the consensus of all parties involved in the value chain of the product or service in question.

The first pillar of the standardisation system is the participation of stakeholders, such as representatives of business and industry (especially SMEs), consumers' organizations, professional bodies, assessment, testing and inspection bodies, environmental and societal organizations, public authorities and enforcement bodies, trade associations, trade unions, academy and university, research organizations, etc. This expert, open and multilateral participation is the basis for the global acceptance, the reliability and the quality of the published standards.

The second pillar of the standardisation is that the standards must be developed by a recognized body to ensure that the required rules of transparency, consensus and independence are respected. These bodies can be national, European, or international. For the HYPERNEX objectives, this chapter will focus on European standardisation and its standardisation bodies CEN (European Committee for Standardisation) for the non-electrotechnical field and CENELEC (European Committee for Electrotechnical Standardisation) for the electrotechnical field.

As defined by CEN and CENELEC, the objective of European standardisation is to agree on common specifications and/or procedures that respond to the needs of business and meet consumer expectations. These standards are prepared by the Standardisation Technical Committees operating under its own field and scope, the identified standards is developed and executed for.

Technical Committees work on the basis of national participation by the CEN Members, where delegates represent their respective national point of view. This principle allows at taking balanced decisions reflecting a wide consensus.

The development and use of standards are a common practice in all sectors (industry, services, management, etc.). Figure 27 shows the figures about active European standards and Figure 28 the publications of European standards by August 2021 and activity sector.

In particular, the railway sector is fully committed to collaborate with standardisation activities. In June 2021, the Shift2Rail Joint Undertaking, CEN and CENELEC signed a Memorandum of Understanding (MoU) that will bring forward the standardisation work on the railway sector in Europe. Currently, there are two Standardisation Technical Committees working on railways systems and components at European level, with a total of 478 standards published and 180 under development (Table 3).

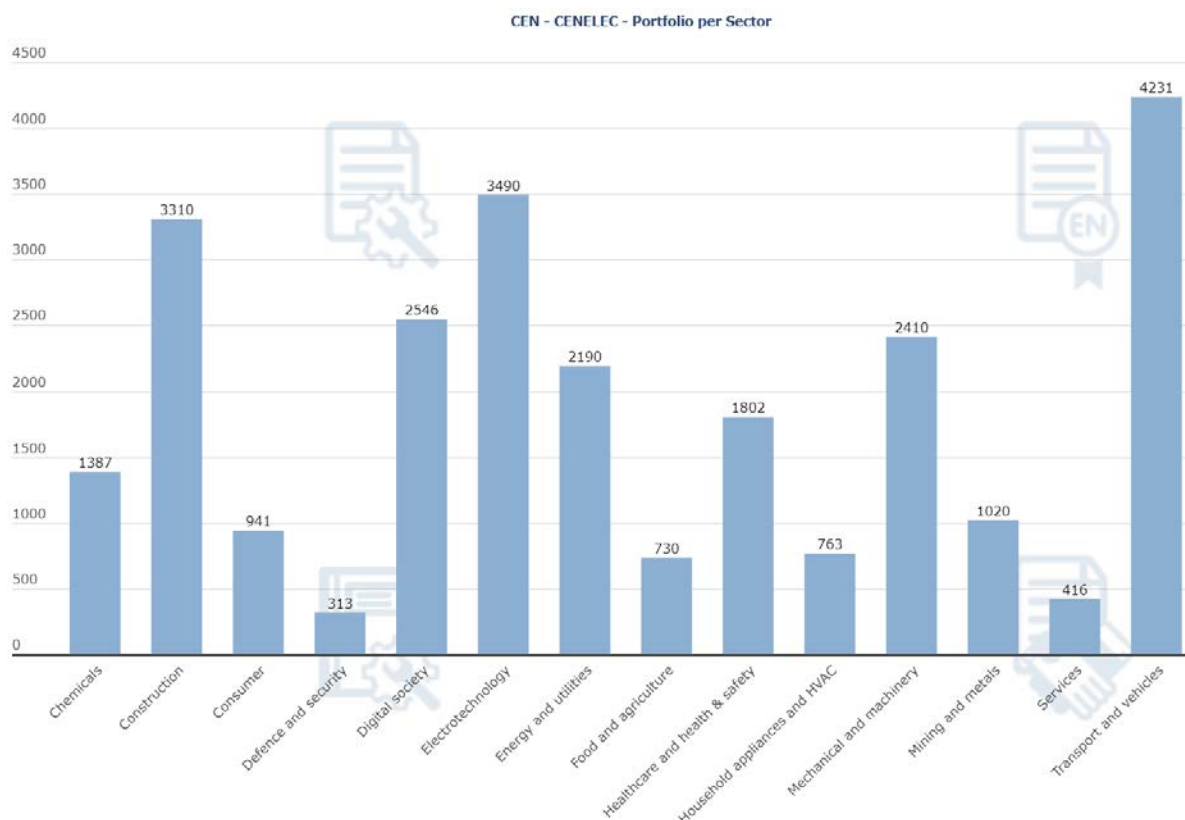


Figure 27. European standards, July 2021. Source: CEN-CENELEC

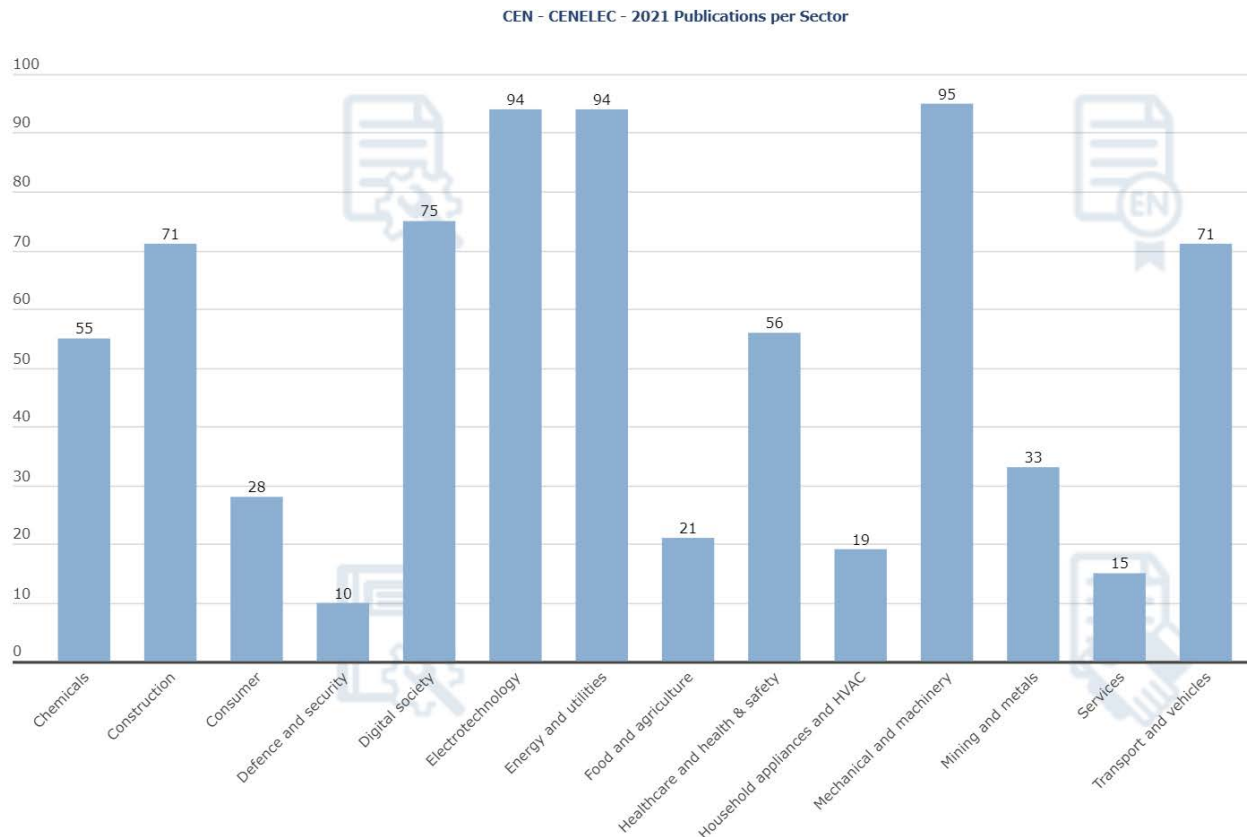


Figure 28. European standards published from January 2021 to July 2021. Source: CEN-CENELEC

Table 3 European Standardisation Technical Committees. Source: CEN-CENELEC

Standardisation Technical Committee	Published standards	Standards under development
CEN/TC 256 Railway applications	259	150
CENELEC/TC 9X Electrical and electronic applications for railways	219	30

2.5.1.1 Standardisation on Hyperloop

In February 2020 the first Standardisation Technical Committee was created in Europe, CEN-CENELEC/JTC 20 *Hyperloop systems*. During 2020 and 2021 a series of meetings has taken place to define the structure, the priorities and set the work-programme.

Following the stakeholder's participation principle, through their national delegations representatives from the Hyperloop industry, railway operators, manufacturers, universities, technological centres, etc. are participating in CEN-CENELEC/JTC 20 and its working groups. It is important that all the Hyperloop promoters active in Europe are proactively participating.

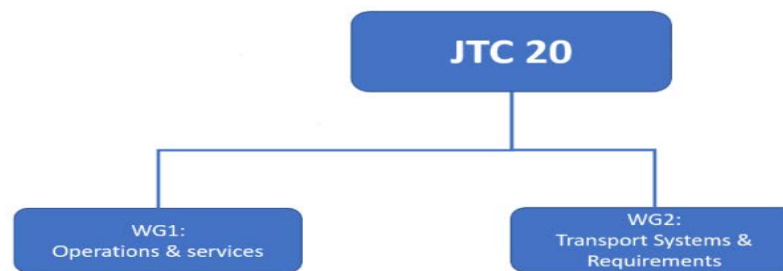


Figure 29. Approved structure of CEN-CENELEC/JTC 20

The current situation of CEN-CENELEC/JTC 20 as approved in its last plenary meeting celebrated on the 15th July 2021 is structured in two working groups as shown in Figure 29 and a work-programme with five work items under development, as shown in Table 4.

Table 4 CEN-CENELEC/JTC 20 work-programme

Work item	Scope of the work item
JT020001 Hyperloop transport services	Hyperloop transport services are designed to support passenger transport and cargo transport. For each of the transport services, user/customer requirements and expectations are different. This document will define the hyperloop transport services supported by a hyperloop system and provides means for characterisation and description of these services. The characterization will consider the technical as well as operational/commercial features of each transport service.
JT020002 Standards inventory and roadmap	This document will be a Technical Report. The objective is to list the relevant standards from various fields and provides a standardization roadmap for hyperloop systems. The roadmap will provide guidance on the applicable standards from various fields, those that need amending and the new-to be developed standards.
JT020003 Hyperloop systems aspects. Reference architecture	This document will specify the reference architecture for a hyperloop system. It will specify the functions of each subsystem to define the purpose of each block, its different possible implementations, and will highlight how the subsystems support each other. The interfaces of the transportation system will be listed, whether it be internal interfaces or exterior interfaces. The characterization considers the technical as well as operational features of the transport service.
JT020004 Hyperloop systems. General requirements	This document will provide a general view of the most relevant requirements to ensure safety, reliability, system automation, security, comfort, interoperability and operations of the hyperloop system used for the transport of passengers and goods. This document will be the basis to set the general common requirements for the hyperloop system as a whole.
JT020005 Hyperloop vocabulary and definitions	The document will provide a nomenclature and definitions needed for hyperloop system related standards. This document will be the basis to set the general vocabulary definitions for the hyperloop system as a whole.

2.5.2 Standardisation and regulation

As the European Commission states, standardisation has played a leading role in creating the EU Single Market. Standards support market-based competition and help ensure the interoperability of complementary products and services. They reduce costs, improve safety and enhance competition. Due to their role in protecting health, safety, security and the environment, standards are important to the public. The EU has an active standardisation policy that promotes standards as a way to better regulation and enhance the competitiveness of European industry.

European Standardisation is a key instrument for the consolidation of the Single Market and for strengthening the competitiveness of European companies, thereby creating the conditions for economic growth. Communication between the national standardisation bodies, the European standardisation organisations and the European Commission about their current and future activities as well as the standstill principle (withdrawal of national standards after the publication of a new European standard) applicable to the national standardisation bodies within the framework of the European standardisation organisations is crucial for the objective of the Single Market.

Standards can be used to improve safety and performance, raise levels of energy efficiency and protect consumers, workers and the environment. They complement European and national policies in these areas and make it easier for companies and other actors to respect relevant legislation. The collaboration between standardisation and regulation is developed by the so called *New Approach*. The basic principles of this new approach are the following:

- The EU adopts legislation (EU Directives/Regulations) that defines essential requirements, in relation to safety and other aspects of public interest, which should be satisfied by products and services being sold in the Single Market;
- The EC issues standardisation requests to the European Standardisation Organizations, which are responsible for preparing technical standards that facilitate compliance with these essential requirements;
- Public authorities must recognize that all products manufactured (and services provided) in accordance with harmonized standards are presumed to conform to the essential requirements as defined by the relevant EU legislation.
- European Standards remain voluntary and there is no legal obligation to apply them. Any producer (or service provider) who chooses not to follow a harmonized standard is obliged to prove that their products (or services) conform to the essential requirements.

In July 2021, a total of 3.461 European standards were cited as harmonised standards in the Official Journal of the European Union. In particular, for the railway sector, the reference legislation under the new approach is Directive (EU) 2016/797 on the interoperability of the rail system within the European Union (European Union, 2016). Under this Directive 144 standards are cited as harmonised.

This approach is applied since 1985. From then, the process has evolved and improved to adapt to the new necessities and provide the best response. On October 2015, the EC presented the new Single Market Strategy (COM/2015/0550 final), being one of the objectives to modernise the

standardisation system. For that purpose, the Joint Initiative on Standardisation was published in June 2016. This revision that provides response to the new strategies of the EU adds a new key point to all the above mentioned: *innovation*. Standards are keys for innovation and progress in the Single Market and are essential to supporting European competitiveness, jobs and growth.

2.5.2.1 Regulation on hyperloop

Up to the moment, no regulatory framework exists for the Hyperloop. In Deliverable D.2 of the HYPERNEX project, an overview of the situation of the legislation is included. The European Commission has requested a study on the Hyperloop regulatory framework that was completed in March 2021. In the consultation with the Hyperloop stakeholders it has been highlighted the necessity of having legislation in time for the deployment of the Hyperloop system.

2.5.3 Standardisation and innovation

Standards are part of the knowledge economy that underpins European industry and society. They facilitate innovation and promote the adoption of new technologies. The standards traditionally have focused on in-market products and services. In the last years their potential as an innovation tool has been highlighted and strengthened. They promote innovation, facilitate the adoption of new technologies and provide a bridge between research and innovation activities and the market. These facts have been recognized by the European Union within Horizon 2020, from the early policy communications to several specific references in all work programmes from 2014 to 2020.

Finally, in the EC Communication on the current framework programme FP9 *Horizon Europe*, standardisation is recognised as a tool for supporting the exploitation of the Research and Innovation results (European Commission, 2021). The use of existing standards and the development of new ones in innovative environments optimize the resources needed and facilitate the introduction of the innovative concept into the market because:

- The use of standards in the earliest possible stages of the innovation projects give access and information to the state of the art and avoids work duplication.
- Designing upon standards ensures compliance with market conditions and grants safety and interoperability.
- Producing upon standards ensures comparability, compatibility and interoperability, which generate users' confidence.

2.5.3.1 Limitations

In European Commission's *Interim evaluation of Horizon 2020*, standardisation is considered a critical factor in competitiveness, together with interoperability and norms. Nevertheless, the participation in standardisation activities and the objective of developing new standards is limited.

In order to help in the awareness of researchers about the need of standardisation to be included in R&D projects, the EC launched the BRIDGIT and BRIDGIT2 Projects. These projects have sought for the research and innovation community to fully engage with standardisation. The project also collected compelling evidence that standardisation facilitates the market uptake of outcomes from

H2020 and earlier framework programmes and thus also should have has an important role to play in FP9.

As outcome, in 2018 CEN and CENELEC have defined an Innovation Plan aiming at strengthening their relationship with researchers and innovators. This Innovation Plan identifies 9 specific actions, addressing 3 strategic goals:

- Recognizing contributions from Research;
- Fast-track approach;
- Recognition and support from Institutions.

It is usually considered controversial to use together the terms patents and standards. For many researchers and companies, it is considered to be contradictory. In particular, when preparing standards:

- A company that makes important investments in developing new technologies or products wants to avoid using standardisation because of internal knowhow.
- The experts want to include the best technology, but it is protected by patents.

For the first case, the standards are more and more based on performance rather than on technology description. For the second case, in order to preserve the universal approach of standards, while also respecting the rights of the patent holders, CEN and CENELEC have developed an Intellectual Property Rights (IPR) policy under the provision of the CEN-CENELEC *Guide 8. Standardisation and intellectual property rights* (CEN-CENELEC, 2019).

The purpose of the CEN-CENELEC Guide 8 is to provide practical guidance to the participants in technical bodies on how to deal with patent-related matters. In particular, encourages the early disclosure and identification of patents that may relate to standards under development and the conditions for the patent holder. In the Horizon 2020 program, standardisation was named for the first time as a valuable parameter to be considered when approving the innovation request proposal. In the Horizon Europe Programme Guide (European Commission, 2021) there is a specific Clause *Why is it important to consider standardisation when drafting a proposal* and the recommendation is: *If the project is relevant for standardisation it is advised for applicants to involve standard development organisations in the consortium in order to facilitate the valorisation of project results through standardisation.*

There is a common agreement that funds for developing Hyperloop is a necessity. The HYPERNEX project is the first project funded by the EC under Shift2Rail for it and more specific calls will be needed in the future to obtain the goal of the deployment of the safest and most interoperable Hyperloop system. On the other hand, developing standards for Hyperloop is necessary and should be considered in the calls for the projects to align with the declared intentions:

- The Commission will provide dedicated support to dissemination, exploitation and knowledge diffusion and put more emphasis on promoting the exploitation of R&I results;

- Standardisation facilitates the deployment of new technologies, interoperability between new products and services. Innovations can more easily gain market acceptance and consumer trust if they comply with existing standards for safety, quality, performance and sustainability.

2.6 Conclusions on Innovative concepts for guided transport modes

The analysis of innovative concepts suitable for guided transport modes has showed clearly that exciting innovations in the rail industry are actively developing and that interested stakeholders are constantly working towards their fruition. Taking a more extensive approach by going beyond just Hyperloop, the results have demonstrated that developments in rail in general are rapidly growing and new ideas are being explored constantly. As a result of that, certain limitations have naturally arisen, such as research gaps regarding particular components or applications of modes of transport. Additionally, a need for a common understanding of certain concepts is essential in order for all stakeholders to collaborate successfully.

3 Hazard identification and safety case approach

3.1 Introduction

In this report is analyzed a generic hyperloop system and identified relevant hazards. To ensure completeness, the analysis is based on looking at different domains relevant for the Hyperloop system. Moreover, different safety case approaches in the different domains are evaluated.

3.2 Regulated and voluntary European railway standards

This analysis gives an overview of regulated and voluntary impacts of European railway standards. The set of standards referred as the pillar of the related safety system to railways are below.

1. EN 50126-1. Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: *Generic RAMS Process*.
2. EN 50126-2. Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 2: *Systems Approach to Safety*.

They are the most generic and significant for the railway as applied in all subsystems of the rail system. The edition of the standard published in 2017 (EN 50126-1 and EN 50126-2) changes and extends some concepts that will play a key role in the development of new products, such as the concept of Safety Integrity Level (SIL).

Other relevant standards for the safety of the railway applications are here below.

3. EN 50128. Railway applications - Communication, signalling and processing systems. *Software for railway control and protection systems*. It should be applied to the development, implementation and maintenance of any software related with safety, aimed at applications of control and protection of the railways. The central concept in this European standard are the five levels of safety integrity of the software (0 being the minimum level and 4 the maximum). The more dangerous consequences of a software failure, the higher the level of safety integrity that would be required. The current version is EN 50128:2012.
4. EN 50129. Railway applications. Communication, signalling and processing systems - *Safety related electronic systems for signalling*. It is applicable to the phases of specification, design, construction, deployment, acceptance, operating, maintaining and codification/extension of comprehensive signalling systems, and it also applies to subsystems and individual products included in a comprehensive system. Its application is usually considered in the development of the hardware, but the new edition of EN 50126 is fully aligned with the current edition of EN 50129:2020.
5. EN 50159. Railway applications – Communication, signalling and processing systems – *Safety-related communication in transmission systems*. If a safety-related electronic system involves the transfer of information between different locations, the transmission system then forms an integral part of the safety-related system, and it shall be shown that the end to end communication is safe in accordance with EN 50129. The transmission system considered in this standard, which serves the transfer of information between different locations, has in general no particular preconditions to satisfy. It is from the safety point of view not trusted, or not fully trusted. The standard is

dedicated to the requirements to be taken into account for the communication of safety related information over such transmission systems. Although the RAM aspects are not considered in this standard it is recommended to keep in mind that they are a major aspect of the global safety.

6. EN 50657. Railways applications. *Rolling stock applications. Software on board*. EN 50657 does not specify the requirements for the development, implementation, maintenance and / or operation of security policies, or protection services. In this sense, since the protection of Information Technology (IT) can affect not only the operation, but also the functional safety of the system, to ensure the protection of Information Technology, IT protection specific rules must be applied (ISO / IEC standards of the 27000 series, ISO / IEC / TR 19791, as well as the IEC 62443 series). These standards, which are exclusively applicable in the railway field, are based on the international standards IEC 61508 Functional Safety of Electrical / Electronic / Programmable Electronic Safety Related Systems.
7. EN 50155. Railway applications. *Electronic equipment used on rolling stock*. Sets requirements related to aspects such as environmental operating conditions, electrical conditions, electromagnetic compatibility, reliability and maintainability, design, components, construction, safety, documentation, tests, etc. This standard can be used as a code of good practice to cover the *technical safety requirements*.
8. EN 50122. Railway applications - Fixed installations - *Electrical safety, earthing and the return circuit*. This standard is in three parts. Part 1: Protective provisions against electric shock; Part 2: Provisions against the effects of stray currents caused by DC traction systems and Part 3: Mutual interaction of AC and DC traction systems.

There are other documents not defined as European Standards but taken into account for Railway Safety. A significant actor in Europe are the European Railway Agency (ERA) and the National railway safety authorities, created to promote a harmonized approach to railway safety and to act as the European Authority under the Fourth Railway Package issuing vehicle (type) authorizations and single safety certificates, while improving the competitive position of the railway sector. Relevant issues for the railway community are the following:

- *Technical Specifications for Interoperability (TSIs)* define the technical and operational standards that must be met by each subsystem or part of subsystem in order to meet the essential requirements and ensure the interoperability of the railway system of the European Union.
- *Safety Management System* to ensure that the organisation achieves its business objectives in a safe manner and complies with all the safety obligations that apply to it.
- *Common Safety Methods (CSMs)* describe how safety levels should be fulfilled, the achievement of safety targets and compliance with other safety requirements.

3.3 EN 50126 overview

The EN 50126 standard is the standard framework of reference in the railway industry for the definition of the terms of reliability, availability, maintainability and safety; therefore, the link with the operation and service parameters that safely safeguard the operation and use of components and systems; being of special relevance the treatment given in this standard on RAM engineering

is on the concept, analysis and management of *breakdowns*. That is, the management of the loss of the ability to function in the required way of a product, system or installation.

The concept of failure is an event with four relevant components to carry out a risk analysis and its mitigation through containment and protection actions (FMECA studies, or hazard analysis such as PHA or Hazard Log, typically enter this activity).

These four components correspond to the categories for classifying failures based on their severity in terms of their effects on people and the environment:

- Catastrophic: deaths, also multiple serious injuries and/or extreme damage to the environment;
- Critical: a single victim, also together with a serious injury and/or severe and significant damage to the environment;
- Marginal: minor injuries and/or minor damage to the environment;
- Negligible: possible minor injury.

The list of threats is recorded in the hazard record (Hazard Log). Special attention will be paid to identifying threats that have technical characteristics: deficiencies, insufficiencies or failures that can be detected in the design, construction or manufacturing, installation, testing, implementation, regulation or subsequent verification processes. Therefore, the deficiencies will be referenced:

1. Gaps of outdated or inadequate standards;
2. Gaps of or deficiencies in technical specifications or procedures;
3. Failure to carry out or insufficient acceptance tests for installations or rolling stock;
4. Gaps of reviews or verifications;
5. Incorrect or inconsistent data. Lack of verification;
6. Gaps in previous studies.

The 50126 standard is made up of two parts (summary of the terms of reference for CENELEC 50126-1:2017 and 50126-2:2017).

Part 1 of EN 50126 considers RAMS, understood as reliability, availability, maintainability and safety and their interaction and considers the generic aspects of the RAMS life cycle. The guidance in this part can still be used in the application of specific standards; it defines: a process, based on the system life cycle and tasks within it, for managing RAMS; a systematic process, tailorable to the type and size of the system under consideration, for specifying requirements for RAMS and demonstrating that these requirements are achieved; addresses railway specifics; enables conflicts between RAMS elements to be controlled and managed effectively; it does not define: RAMS targets, quantities, requirements or solutions for specific railway applications; rules or processes pertaining to the certification of railway products against the requirements of this standard; - an approval process for the railway stakeholders. This part 1 of EN 50126 is applicable to railway application fields, namely Command, Control and Signalling, Rolling Stock and Fixed Installations and specifically: to the specification and demonstration of RAMS for all railway applications and at all levels of such an application, as appropriate, from complete railway systems to major systems

and to individual and combined subsystems and components within these major systems, including those containing software; in particular: to new systems; to new systems integrated into existing systems already accepted, but only to the extent and insofar as the new system with the new functionality is being integrated. It is otherwise not applicable to any unmodified aspects of the existing system; as far as reasonably practicable to modifications and extensions of existing systems already accepted, but only to the extent and insofar as existing systems are being modified. It is otherwise not applicable to any unmodified aspect of the existing system; at all relevant phases of the life cycle of an application; for use by railway duty holders and the railway suppliers. It is not required to apply this standard to existing systems which remain unmodified, including those systems already compliant with any former version of EN 50126. The process defined by this European Standard assumes that railway duty holders and railway suppliers have business-level policies addressing Quality, Performance and Safety. The approach defined in this standard is consistent with the application of quality management requirements contained within EN ISO 9001.

Part 2 of EN 50126 considers the safety-related generic aspects of the RAMS life-cycle; defines methods and tools which are independent of the actual technology of the systems and subsystems; provides: the user of the standard with the understanding of the system approach to safety which is a key concept of EN 50126; methods to derive the safety requirements and their safety integrity requirements for the system and to apportion them to the subsystems; methods to derive the safety integrity levels (SIL) for the safety-related electronic functions. Note this standard does not allow the allocation of safety integrity levels to non-electronic functions. Provides guidance and methods for the following areas: safety process; safety demonstration and acceptance; organisation and independence of roles; risk assessment; specification of safety requirements; apportionment of functional safety requirements; design and implementation. It provides the user of this standard with the methods to assure safety with respect to the system under consideration and its interactions; it provides guidance about the definition of the system under consideration, including identification of the interfaces and the interactions of this system with its subsystems or other systems, in order to conduct the risk analysis; it does not define: RAMS targets, quantities, requirements or solutions for specific railway applications; rules or processes pertaining to the certification of railway products against the requirements of this standard; an approval process by the safety authority. This part 2 of EN 50126 is applicable to railway application fields, namely Command, Control and Signalling, Rolling Stock and Fixed Installations and specifically: to the specification and demonstration of safety for all railway applications and at all levels of such an application, as appropriate, from complete railway systems to major systems and to individual and combined subsystems and components within these major systems, including those containing software, in particular: to new systems; to new systems integrated into existing systems already accepted, but only to the extent and insofar as the new system with the new functionality is being integrated. It is otherwise not applicable to any unmodified aspects of the existing system; as far as reasonably practicable, to modifications and extensions of existing systems accepted prior to the creation of this standard, but only to the extent and insofar as existing systems are being modified. It is otherwise not applicable to any unmodified aspect of the existing system: at all relevant phases of the life-cycle of an application; for use by railway duty holders and the railway

suppliers. It is not required to apply this standard to existing systems that remain unmodified, including those systems already compliant with any former version of EN 50126. The process defined by this European Standard assumes that railway duty holders and railway suppliers have business-level policies addressing Quality, Performance and Safety. The approach defined in this standard is consistent with the application of quality management requirements contained within EN ISO 9001.

3.4 EU 402 Overview

The implementation of Regulation EU 402/2013 establishes uniform criteria on railway safety within the European Union for all its members, for safety management, assessment, and risk control against possible changes. This regulation is mandatory and identifies the changes to be implemented as significant or not significant. The railway system must implement a number of activities to meet the imposed safety requirements. The changes that are included under this regulation are changes of a technical nature, operating conditions and organizational changes within the railway administration.

The regulation establishes codes of practice to accept the risk of a significant change by comparison with similar parts of the rail system or by estimates of it. Where a proposed change has an impact on safety, the Common Safety Methods, CSM, require deciding the significance of the change based on the criteria set out in the EU 402/2013 Implementation Regulation (Figure 30). The CSM does not indicate how to use these criteria or in what weighting. These criteria can be summarized as follows:

- Novelty used in the implementation of the change;
- Consequence of the failure: the credible worst-case scenario for the evaluation is established;
- Complexity of Change;
- Reversibility: the inability of the system to return to its previous state;
- Additionally: recent system updates or changes taken into account,
- Monitoring: possibility throughout the life cycle and making the appropriate decisions.

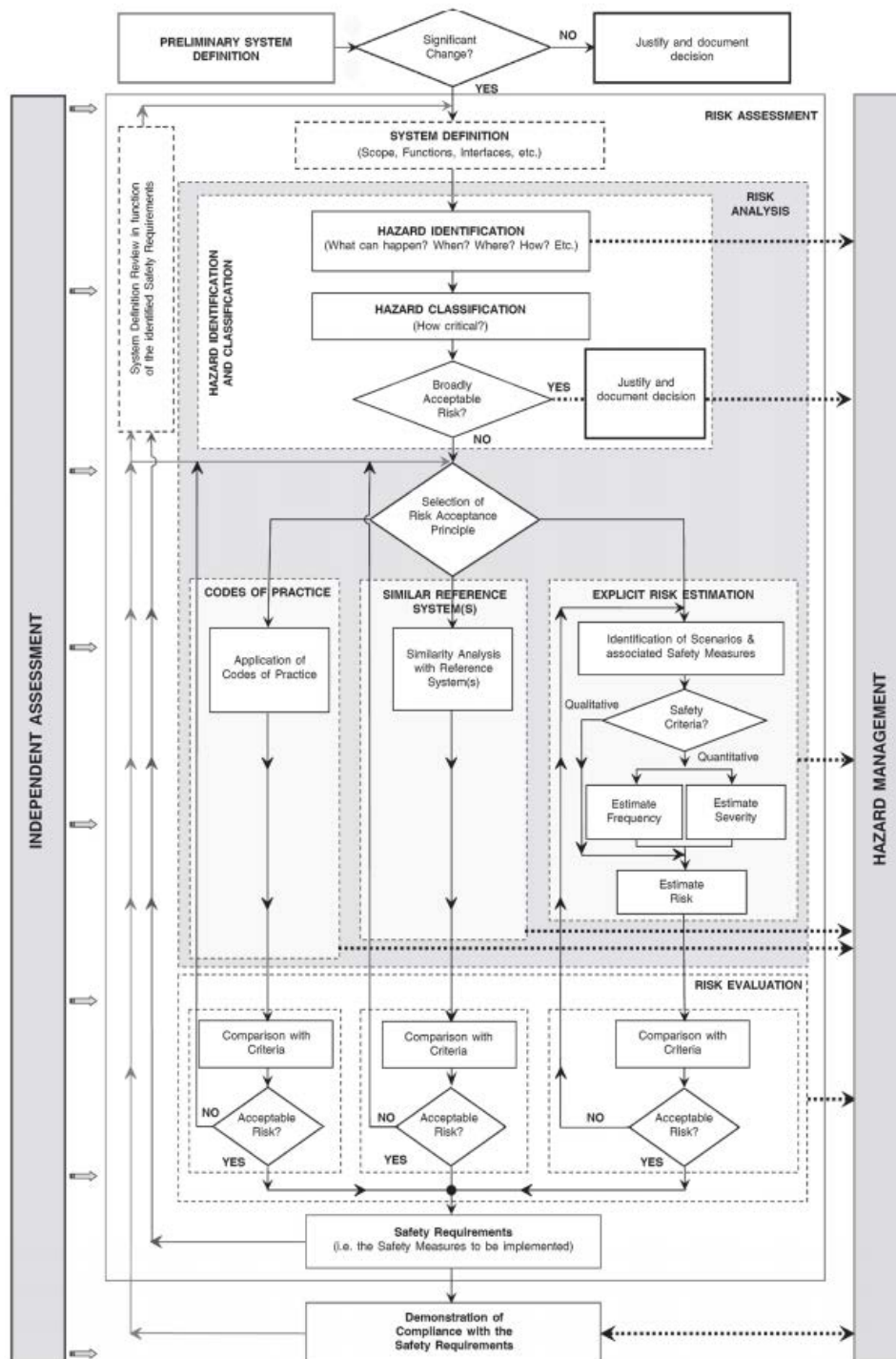


Figure 30: EU402/2013 Safety Common Methods. Risk management process and independent assessment. Source: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:121:0008:0025:en:PDF>

In this framework, EN 50126 is responsible for describing the methods to be used to specify and demonstrate the Reliability, Availability, Maintainability and Safety (RAMS) of a rail system, defined as follows:

- *Reliability*: probability that an element can perform a required function under certain conditions during a given time interval;
- *Availability*: ability of a product to be in a position to perform a required function under certain conditions at a given time or during a specified time interval, assuming that the required external resources are provided;
- *Maintainability*: probability that a given active maintenance action, corresponding to an element under given conditions of use, can be carried out at a set interval of time when maintenance is performed under established conditions and established procedures and resources are used;
- *Safety*: absence of an unacceptable risk of failure.

A deficiency in security and availability requirements or poor conflict management can prevent a reliable and quality system from being achieved. To prevent this from happening, it is necessary to properly control all reliability and safety requirements and with proper management of operation and maintenance, as these are the factors that directly affect safety and availability. Figure 31, taken from the EN 50126 standard, shows schematically the way in which the elements of the railway RAMS are related.

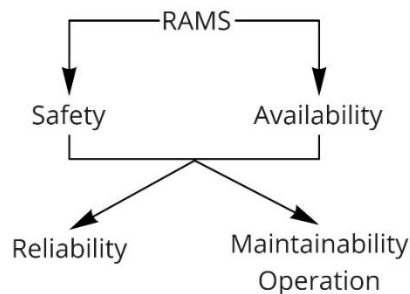


Figure 31: Interaction of RAMS elements. Source: EN 50126

The lifecycle approach provides a structure for planning, managing, controlling, and monitoring all aspects of a system, including RAMS, as the study system progresses through the lifecycle. The objective of the RAMS process is to reduce the incidence of failures and/or their consequences throughout the life cycle and to minimize the residual risk resulting from these errors. The lifecycle model is shown in Figure 32.

The EN 50126 defines the Safety Integrity Level (SIL) linked to a probability objective or Tolerable Hazard Risk (THR). There are four levels of SIL depending on the damage that systems can cause within the sector: 1, injuries to people, 2, serious injuries, 3, death to a person, 4, deaths to a group of people. When we talk about SIL associated with software, there are 5 SIL levels, the 4 already mentioned and the SIL level 0, which has no effect on the safety of people. THR refers to the failure rate per operating hour. Table 4 shows the allowed THR ranges for each SIL level.

EN 50128 is responsible for describing the actions to be taken to demonstrate the safety of the software and also for the administration of the tools that are used to support the development, programming and monitoring of railway systems. EN 50129 is responsible for describing the security management of hardware architectures and systems. EN 50121, which deals with the problems of electromagnetic compatibility (EMC), both from the point of view of the radiation emitted from the railway system to the outside world and the environment towards the railway system immunity, affecting train and fixed equipment.

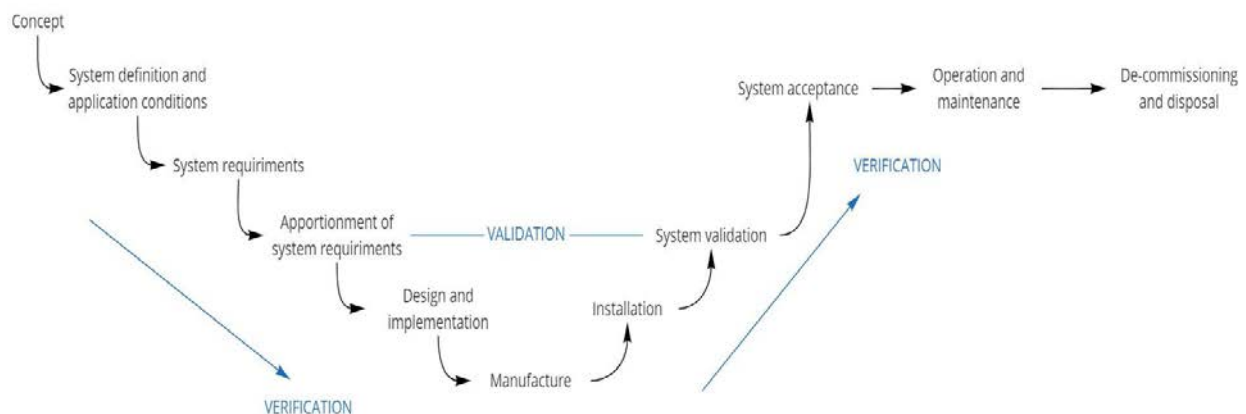


Figure 32: V life cycle according to EN 50126

Table 4: Tolerable Hazard Rate (THR) and Safety Integrity Level (SIL)

THR (h ⁻¹)	SIL
$10^{-9} \leq \text{THR} < 10^{-8}$	4
$10^{-8} \leq \text{THR} < 10^{-7}$	3
$10^{-7} \leq \text{THR} < 10^{-6}$	2
$10^{-6} \leq \text{THR} < 10^{-5}$	1

3.5 Market acceptance under safety condition

3.5.1 Safety case approach

In the modern safety management framework, the market acceptance is strictly conditioned to the permanent fulfillment of safety conditions, which permeates all the lifecycle phases. In particular, the pre-condition demonstration of safety case is to argue that a system is safe in the same way as one would do in a court of law, thus the name *safety case* itself.

The manufacturer should normally start to develop the safety case already in the concept phase. But this depends on the context, complexity and novelty of the product and system. The safety case should be read by the developers, management, the Independent Safety Assessor (ISA), the Notified Body and authorities in some domains like the railway domain in Europe.

Copy from the directive 2016/797 that states that the Notified Body shall be involved already at the design stage: The task of the notified body responsible for the EC verification of a subsystem

shall begin at the design stage and cover the entire manufacturing period through to the acceptance stage before the subsystem is placed on the market or in service. It shall, in accordance with the relevant TSI, also cover verification of the interfaces of the subsystem in question with the system into which it is incorporated.

EN 50126-1:2017 states that the safety case shall be prepared in phase 6 and that it shall be updated at each safety lifecycle phase. In addition, the safety case should be updated when there are special design changes, ODD changes and in general when there are changes in hazards.

The NASA report (NASA, 2017) and the Agile safety case book (Myklebust, Stålhane, 2018) lists relevant benefits when having a safety case approach (Table 5). The benefits of using the Agile safety case in practice together with relevant Agile practices has been described in (Pettersson, Ragnevi, Olsson, 2021) with a positive conclusion.

Table 5 Benefits of using a safety case approach

NASA report	Agile safety case
1. Fundamental Claim: Assurance Cases are Successful where Suitable.	1. Content relevant information for both traditional and agile safety cases according to the Railway and Metro standard EN 50129
2. Benefit Claim: Assurance Cases are More Comprehensive than Conventional Methods Alone.	2. Strengthens communication in all phases of a project and facilitate communication between stakeholders
3. Benefit Claim: Assurance Cases Improve the Allocation of Responsibility over Prior Norms.	3. Easily navigate the status of the safety case
4. Benefit Claim: Assurance Cases Organize Information More Effectively than Conventional Methods.	4. Improved communication of the progress of the project
5. Benefit Claim: Assurance Cases Address Modern Certification Challenges.	5. Less time used on the development of the safety case and less documentation needed
6. Benefit Claim: Assurance Cases Offer an Efficient Certification Path Compared to Other Approaches.	6. Manage changes during development and after the first release
	7. Shorter time from the last code is written to the finalization of the safety case
	8. Improved procedure for updates of the software due to security threats

The Commission Regulation (EU) 2016/919 of 27 May 2016 on the technical specification for interoperability relating to the *control-command and signalling subsystems* of the rail system in the European Union lists mandatory standards, according to the requirements set in the directive 2016/797/EC: EN 50126, EN 50128 and EN 50129.

According to the Guide ERA/GUI/07-2011/INT issued by the European Union Agency for Railway where a standard referred to in a TSI contains a reference to another standard, unless otherwise provided in the TSI, this second standard also becomes mandatory. For the control, command and signalling TSI, this is related to the references in the mandatory standards. The references are listed in the normative references of these standards. For safety assessments outside the scope of the TSIs, the term mandatory standards is not used.

EN 50126-1:2017 has defined safety case as: documented demonstration that the product (e.g., a system, subsystem or equipment) complies with the specified safety requirements. The standards further states that the purpose of a safety case is to develop structured arguments supported by evidence, intended to justify that a product or system is acceptably safe for a specific application in a specific operating environment. Other relevant standards that require or mentioned safety or security cases are:

- EN TS 50701:2021 (draft) Railway security (security);
- ISO 26262:2018 Automotive;
- UL 4600:2020 Automotive;
- BSI PAS 1881:2020 Automotive;
- ISO/SAE 21434:2021 Automotive (security);
- Def. 00-55 Defence;
- DO-178C Avionics;
- RTCA DO-303 Avionics.

At a high level, a safety case is a simple thing. The developing company or manufacturer says: *The system is safe because...* Everything after *because* is a safety case. One of the main benefits using a safety case approach is that evidence can be extended to cover safety issues beyond the scope of safety standards. This has also been stated in the ISO 26262 standard. EN 50129:2018 is the only standard that lists detail information regarding the content of a safety case, as described here below.

Part 1 - Definition of system: This chapter shall precisely define or reference the system, subsystem or equipment to which the Safety Case refers, including version numbers and modification status of all requirements, design and application documentation. When the Safety Case is issued or re-issued due to a change or reconfiguration, a delivery sheet or a release note reporting the complete configuration shall be referenced here. The delivery sheet or release note shall also list the current and previous versions of all the modified products and applications. The hazards depend on the system definition and in particular the system boundary, which allows a hierarchical structuring of hazards with respect to systems and sub-systems. It also means that hazard identification and causal analysis shall be performed repeatedly at several levels of detail during the system development.

Part 2 - Quality Management Report: It describes what has been done to ensure that the system has the required quality throughout the stated parts of the safety lifecycle. It includes subchapters as follows: 1) organisational structure; 2) quality planning and procedures; 3) specification of requirements; 4) design control; 5) design verification and reviews; 6) application engineering; 7) procurement and manufacture; 8) product identification and traceability; 9) handling and storage; 10) inspection and testing; 11) non-conformance and corrective action; 12) packaging and delivery; 13) installation and commissioning; 14) operation and maintenance; 15) quality monitoring and feedback; 16) documentation and records; 17) configuration management/change control; 18) personnel competency and training; 19) quality audits and follow-up; 20) decommissioning and disposal; 21) Summary.

Part 3 - Safety Management Report: It shall document the safety activities that have been performed in order to ensure the necessary safety management during the lifecycles and includes the subchapters as follows: 1) Introduction; 2) Safety lifecycle; 3) Safety organisation; 4) Safety plan; 5) Hazard log; 6) Safety requirements specification; 7) System/sub-system/equipment design; 8) Safety reviews; 9) Safety verification and validation; 10) Safety justification (the Safety Case or The Agile Safety Case); 11) System/sub-system/equipment handover; 12) Operation and maintenance; 13) Decommissioning and disposal; 14) Summary.

Part 4 - Technical Safety report: The intention is to present information about the product or system together with its properties and evidence of compliance to test standards. This chapter shall provide an overview description of the design, including a summary of the technical safety principles that are relied on for safety and the extent to which the system/subsystem/equipment is claimed to be safe the following topics for a technical safety report: 1) Introduction; 2) Assurance of correct functional operation; 3) Effects of faults; 4) Operation with external influences; 5) Safety-related application conditions; 6) Safety qualification tests.

Part 5 - Related Safety Cases: Safety systems often rely on the use of safe components, items, products, equipment, subsystems or constituents. This requires corresponding safety cases which will be identified here. Restrictions, limitations, assumptions, approval status and possible restriction of use or safety related application conditions mentioned in those safety cases are recapitulated or commented in this chapter. Related safety cases may refer to certificates for pre-existing items or software and hardware components, since such certificates will themselves be based on documentary evidence of the relevant safety properties. Such documents may be certification report and safety manuals as described below. Pre-existing items or software shall normally also be described in Part 3 regarding verification and validation (Figure 33).

Part 6 - Conclusion: This chapter summarises the evidence presented in the previous parts of the safety case and argue that the relevant system is adequately safe, subject to compliance with the specified application conditions.

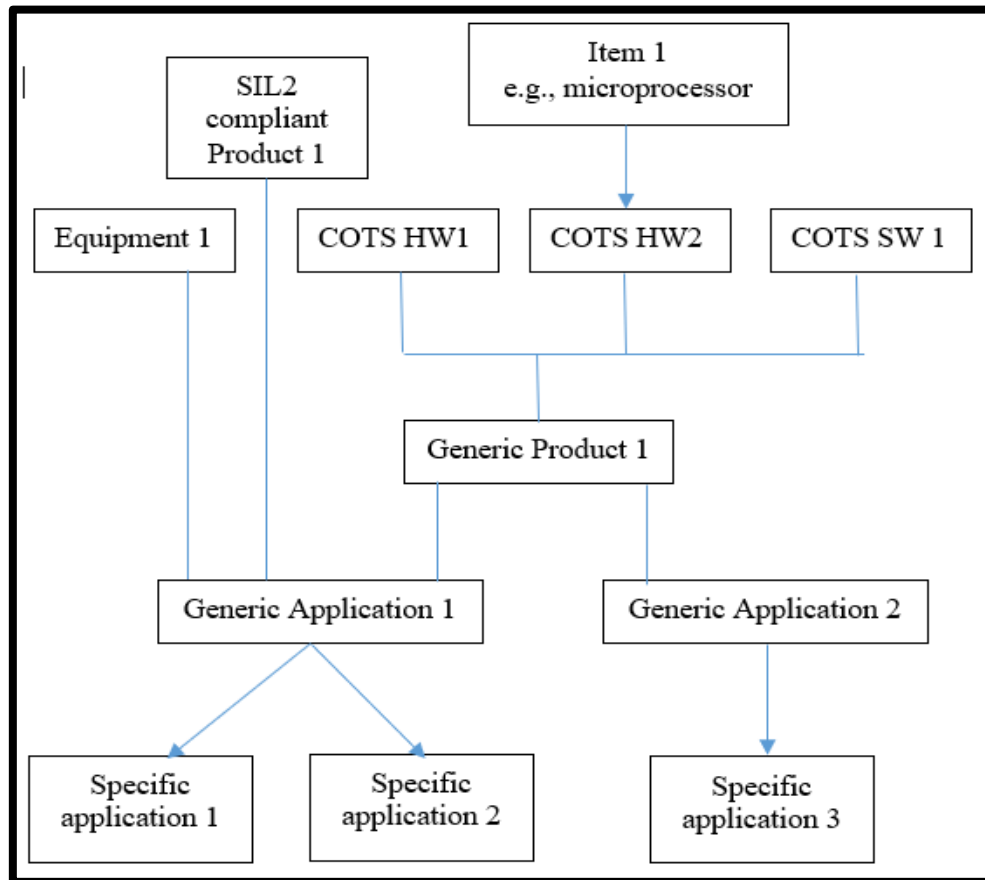


Figure 33: Example of related safety case hierarchy

3.5.2 Approach in the railway domain

The acceptance of a safety-related product in the railway domain is strongly constrained by the mechanism to define risk management and can be followed from EN 50126-1 and EN 50126-2 according to EU Regulation 402/2013 modified by EU Regulation 1136/2015. This takes into consideration the action of an accredited entity under EN ISO/IEC 17020 for those products that are not involved in the interoperability domain or EN ISO/IEC 17065 acting as a Notified Body or Designated Body when the product is affected by the interoperability. The following approach explains in short terms the market requirements. Notified Bodies assess whether subsystems/interoperability constituents (ICs) are in conformity with the essential requirements in European TSIs. Designated Bodies perform this role concerning national rules. It is not certification of the TSIs / national standards but certifying that ICs and subsystems are in conformity with EU (TSIs) / national requirements and rules.

The legal framework in railway safety is represented by the two main directives:

- Directive (EU) 2016/797 of the European Parliament and the Council of 11 May 2016 on the interoperability of the rail system within the European Union;
- Directive (EU) 2016/798 of the European Parliament and the Council of 11 May 2016 on railway safety.

Under this legal framework, a product requires actions to get the fully compliance and acceptance according to the approach defined in Figure 34, whereas the certification entities are:

- Notified Bodies (NoBo): notified by the Member States to the Commission and to the rest of the Member States, for the certification of the Technical Specifications for Interoperability (TSIs).
- Designated Bodies (DeBo): notified to the Commission for the certification of national standards.

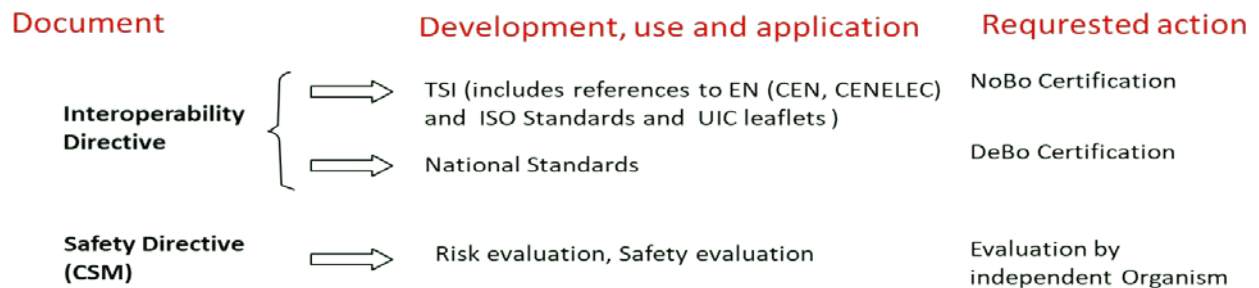


Figure 34: Documents, developments and requested actions

In the sense of Technical Competence demonstration, the Interoperability Directive does not require the accreditation of NoBo or DeBo by the National Accreditation Bodies under EN ISO/IEC 17065. These are part of the European Cooperation for accreditation applying common criteria for the accreditation of certification bodies.

In the same terms of Directive (EU) 2016/798 of the European Parliament and the Council of 11 May 2016 on rail safety, the demonstration of technical competence under the EN ISO/IEC 17020 accreditation is a part of the European cooperation for accreditation. To understand the action of each one of the directives in the complete life cycle defined in EN 50126-1, Figure 35 describes the implication of actions and the map of actors in the certification under TSIs, while the subdivision of subsystems follows the scheme of Figure 36, which can be extended to any time and any component of the railway system, including urban railways according to article 2 of the Interoperability Directive.

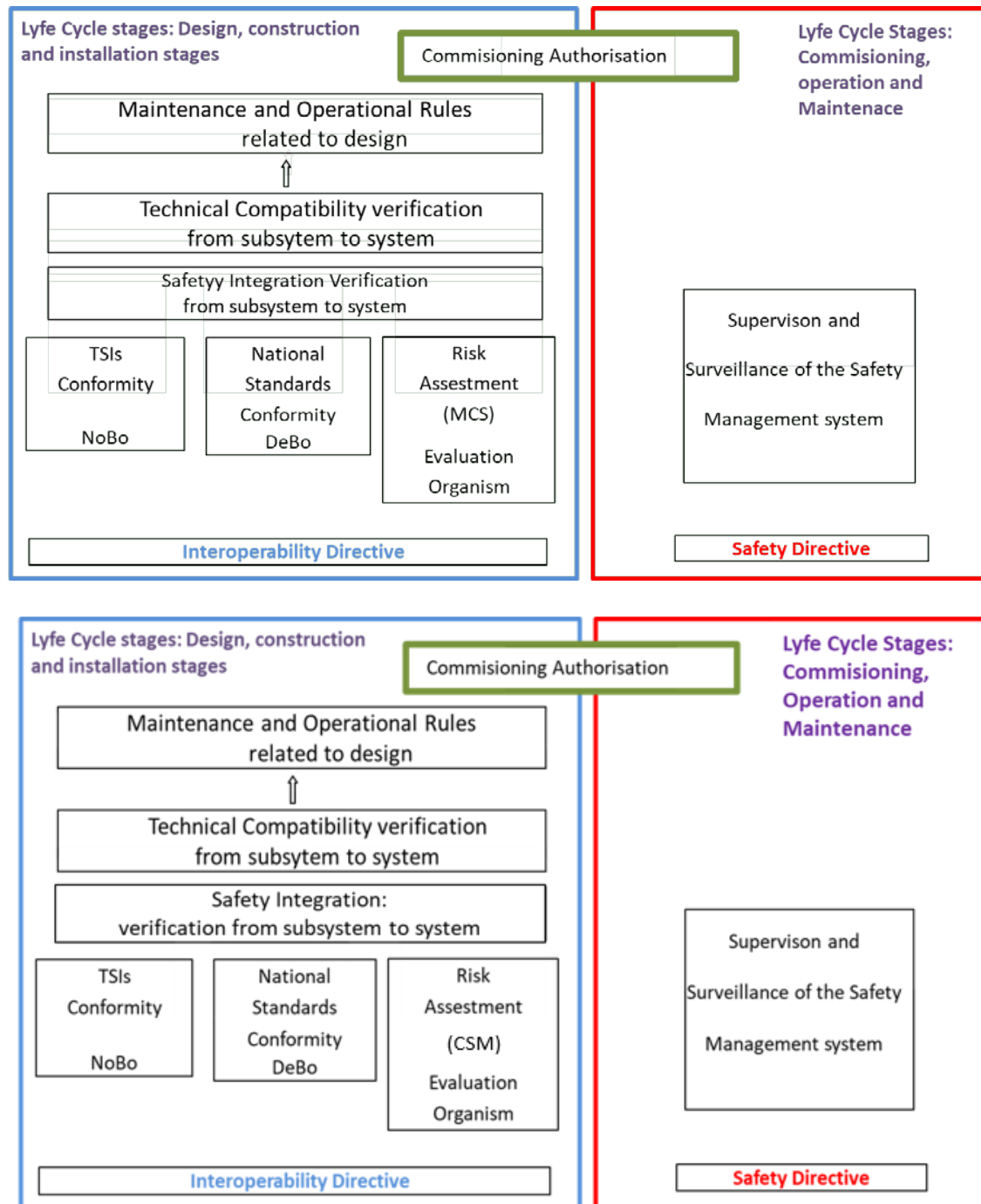


Figure 35: Life cycle scheme in EU directives scope correspondences

The question is *what is the process to follow for the acceptance of a product according to the type of railway?* The European directives act on the concept of main lines, freight or high speed, as well as urban transport when it can be integrated on these networks, including in these directives the set of harmonized standards. On the other hand, the non-interoperable railway system, where European standards are also applied, such as urban and local networks of the cities, as well as products of the railway industry is not affected by interoperability (Figure 36).

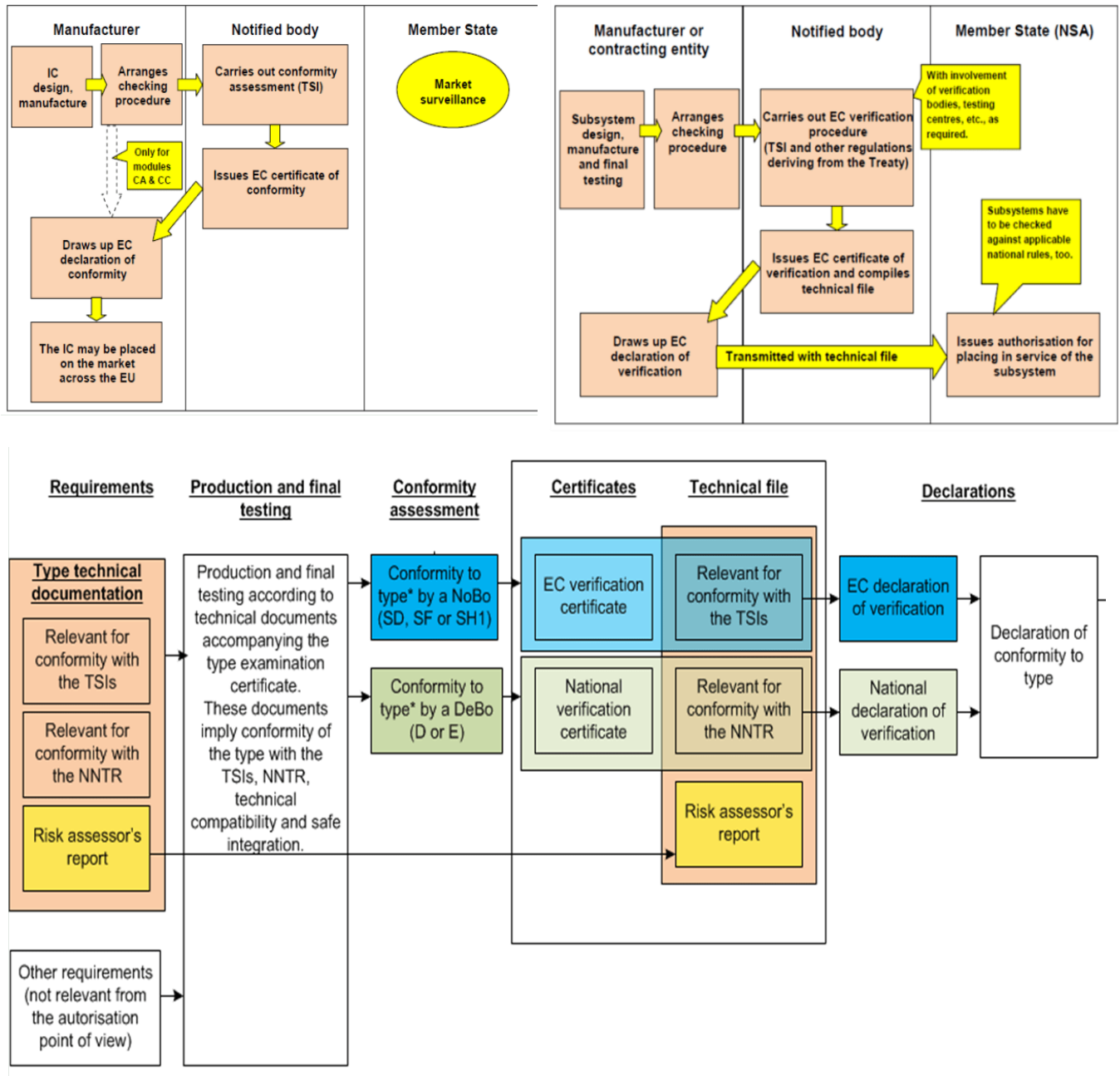


Figure 36: Complete Process for a subsystem: when requirements are not directly supported by TSIs (yellow line), the ISA is requested to be produced under EN50126 or Common Safety Methods from EU Regulation when applicable. The convergence of CSM and EN50126 is integrated from version EN50126-2:2017 and EN50126-1:2017

The safety verification model is apparently contradictory: on one hand the application of the EN 50126 and, on the other one, the development of common safety methods. However, the current version of the EN 50126-1:2017 makes both methods compatible, introduces changes in the definition of life cycle in stages 3, 4, 8, 11 (Figure 37) to find an explicit connection to the common

safety methods when the risk management evaluation is explained. Figure 38 shows the relationship between EN50126 and the CSM.

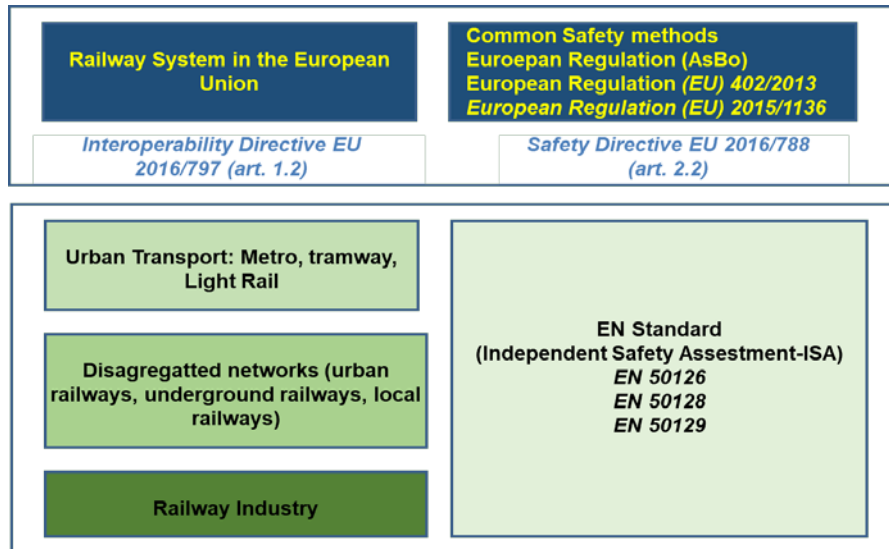


Figure 37: Scheme of rail action in safety according to type of rail system

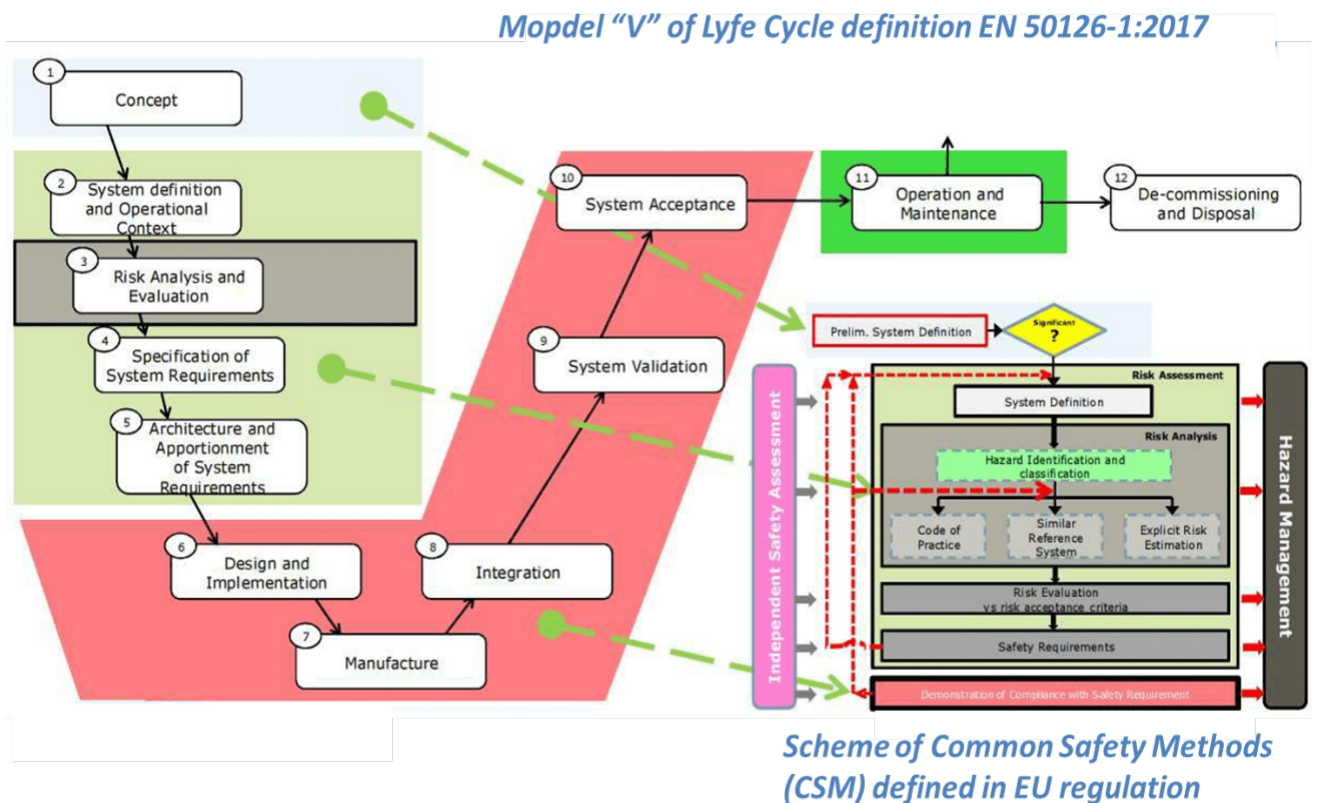


Figure 38: interaction between EN50126 and Common Safety Methods (CSM)

3.6 Methodology proposal for HYPERNEX

In this chapter, we have identified different domains, mainly in the transport field, that are relevant for Hyperloop. As a concept, it shares more features with railways (guided transport) and aviation (low pressure during operation).

3.6.1 Generic functional safety including IEC 61508 related aspects

The functional safety domain is being changed due to several aspects as it has become more relevant for everything from microchips to all domains that moves towards a more autonomous future. Verification, analysis and validation of systems³ becomes more challenging due to modern technologies, such as big data and artificial intelligence. As a result, a new functional safety standard is being developed ISO/IEC TR 5469 *Artificial intelligence - Functional safety and AI systems*. This draft standard also includes it as a part of the development process. In addition, SAE has issued the guideline SAE AIR6988:2021 *Artificial Intelligence in Aeronautical Systems: Statement of Concerns* and ISO/IEC has issued ISO/IEC TR 29119-11:2020 *Software and systems engineering - Software testing - Part 11: Guidelines on the testing of AI-based systems*. Figure 39 represents the *DevOps* approach combined with relevant railway standards.

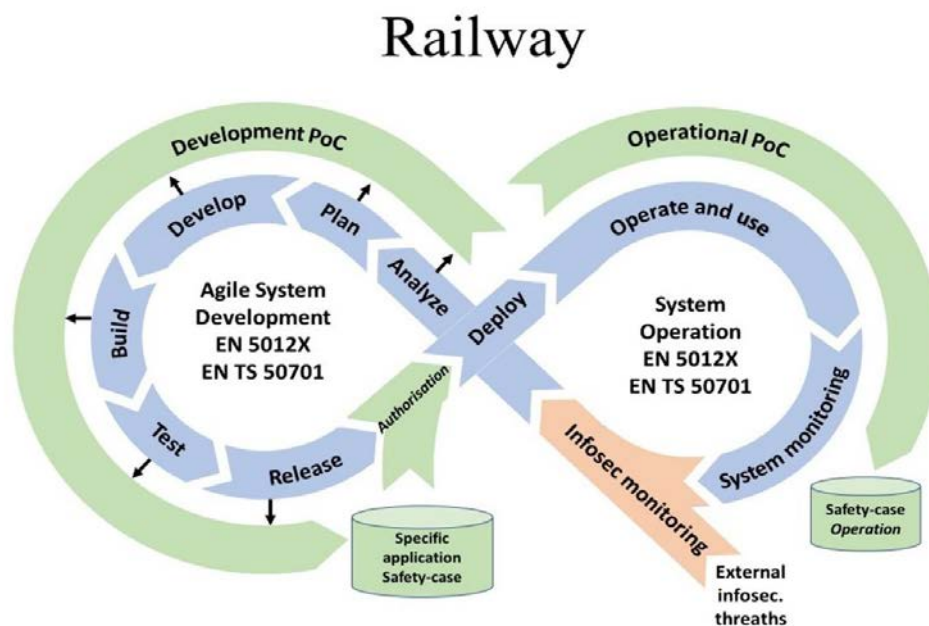


Figure 39: *DevOps* and related railway standards

³ Another very advanced and automated platform for conducting complex failure analyses of multiple interacting digital systems is STPA – at MIT in the US – it has been adopted by many leading technology and innovation companies. STPA = System Theoretic Process Analysis. This methodology is related to a book by the originator, by the title of *Engineering a Safer World*. Extensive open source resources are available at MIT.edu

Hyperloop may base the safety system on relevant certified systems according to the generic standard IEC 61508, which applies to safety-related systems when one or more systems incorporate Electrical and/or Electronic and/or Programmable Electronic (E/E/PE) devices. It covers possible hazards caused by failure of the safety functions to be performed by the E/E/PE safety-related systems, as distinct from hazards arising from the E/E/PE equipment itself (e.g. electric shock). It is generically based and applicable to all E/E/PE safety-related systems irrespective of the application. It is recognized that the consequences of failure could also have serious economic implications. In such cases, the standard could be used to specify any E/E/PE safety-related system used to protect equipment, product or systems. The standard sets out a generic approach for all safety lifecycle activities for E/E/PE safety-related systems that are used to perform safety functions. This unified approach has been adopted to develop a rational and consistent technical policy for all E/E/PE safety-related systems, irrespective of the application sector. A major objective is to facilitate the development of product and the application of international standards based on the IEC 61508 series. For this reason, the first parts of the standard are basic safety publications. The IEC 61508 standard series are now being revised, including several changes that will significantly affect future safety systems. Regarding the safety case, the next edition will not include requirements for a safety case but mention it as one way to prove compliance.

3.6.2 Railway

HYPERNEX applies a Method for Risk Evaluation and Assessment Standards for Railway Systems, aligned to EN 50126 and Common Safety methods (CSM) from EU. This approach promotes the cross-acceptance of the safety cases from other projects, which have been assessed, reviewed and approved by an independent agency or other recognized competent body. In other words, the good practices and expertise from similar actions are valuable if these actions were assessed by a recognized entity. In the Railways safety activities, Regulation (UE) 402/2013, adopted as consequence of the implementation of Directive 2004/49/EC, defines what is the assessment requested and the recognition/accreditation for the entity to produce the assessment. An example is when the entity is accredited against EN-IEC-ISO 17020, taking the role of ISA in terms of CENELEC EN 50126, EN 50128, EN 50129, or EN-IEC-ISO 17065 in the case of NoBo.

The acceptance criteria applied (Figure 40), that maximizes existing work, systems and data, rely on any one of the following principles:

1. Conformity to regulations and standards or to recognized codes of practice: under this principle, a certificate of conformity of a product to a relevant standard is considered as a sufficient proof of safety;
2. Comparison with similar systems operating in a similar environment with a similar mission profile: this principle considers the non-regression with other in-revenue service products or systems used as reference; it allows the re-use of proven technique, technology, equipment or principle for operation and maintenance without re-doing the complete safety demonstration. The reference system(s) shall be approved by client and safety regulatory authority;
3. Explicit risk evaluation: assess qualitatively or quantitatively the risk based on the severity and frequency of the identified hazards; this is justified when the novelty of the action cannot be covered

by codes of practice or similar actions; in this case, the ALARP is the most appropriate method to use due to the traceability of EN50126 safety assessment and a complete ISA is requested for all the processes included in the safety case.

When applying explicit risk estimation, the ALARP principle will be applied to reduce risks, such that the costs of implementing additional risk reduction measures would be grossly disproportionate to the benefits of risk reduction that would be achieved. When a proposed change has an impact on safety, the significance of the change will be decided by expert judgement taking into account the following criteria: 1) failure consequence; 2) novelty; 3) complexity; 4) monitoring; 5) reversibility; 6) additionality.

Once the impact of the safety was decided as *Significant* or *Not Significant*, it is necessary the risk assessment by an independent actor with technical competence demonstrated against:

- Designation of the Authority;
- Accredited technical competence in accordance with EN IEC 17020, Inspection;
- Technical Competence Accredited according to EN IEC 17065, Certification

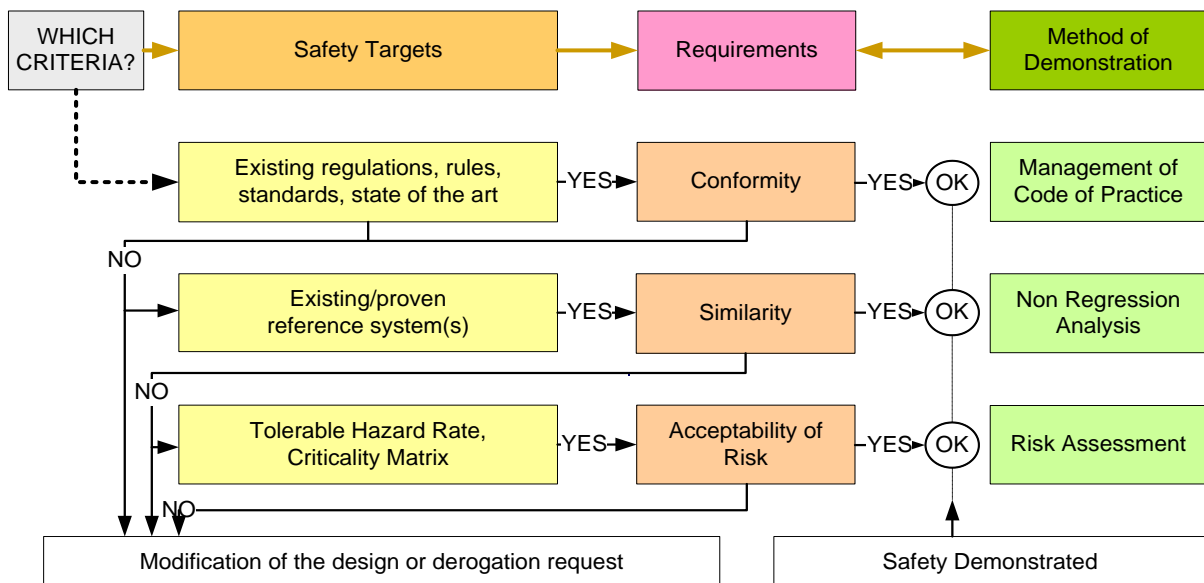


Figure 40: Explanation of the methodology

NoBo or DeBo are the entities used in EU to demonstrate the compliance against the TSI. In this scope, out of the Hyperloop EU regulation domain, it is justified only an Assessment Body (AsBo) or ISA. The AsBo will be more appropriate to the two pillars for risk evaluation based on similar actions or existence of codes of practice. Meanwhile, ISA is oriented to explicit risk evaluation.

3.6.3 Aviation

Historical data (Airbus, 2020) shows how aviation traffic volumes sustain a steady increase of doubling every 15 years. In this regard, the aviation accidents however, show the opposite trend: they have decreased to historical minimum values (Figure 41).

Figure 41, shows there has not been a growth in the number of accidents despite a massive increase in exposure. Focusing too closely on these data may be misleading because the number of fatal accidents varies from one year to another; on the other hand, the increase in the aviation volume is not correlated to the number of fatal accidents. Therefore, it makes more sense to properly assess the sector trend analysis (Figure 42).

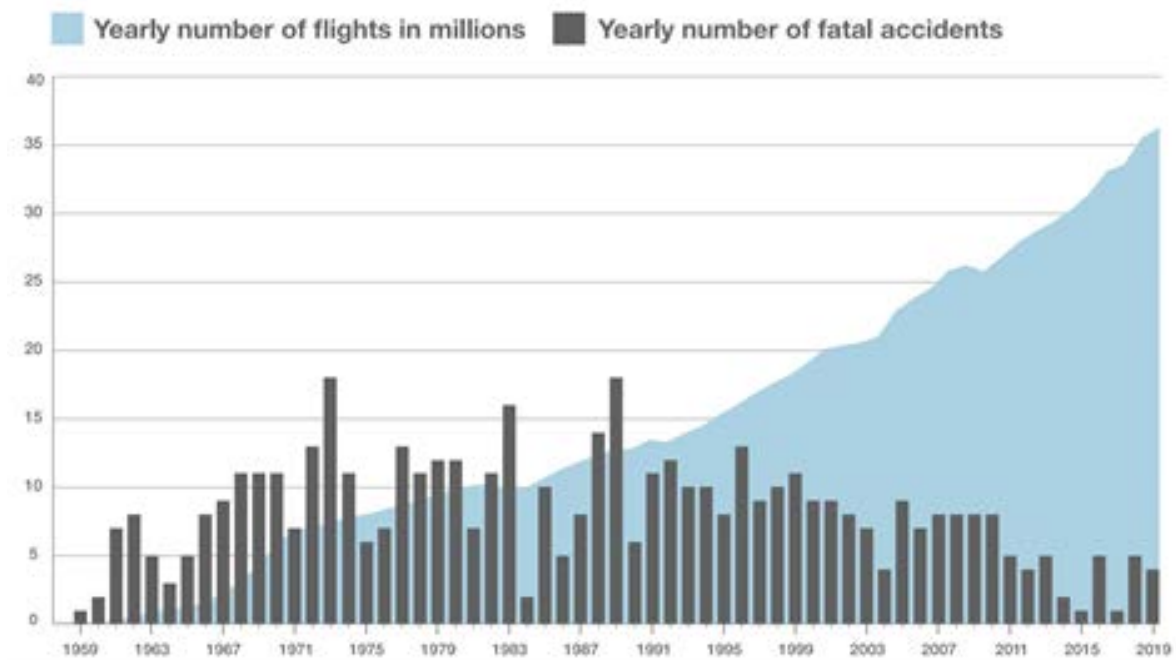


Figure 41: Flights and fatal accidents in the aerospace sector

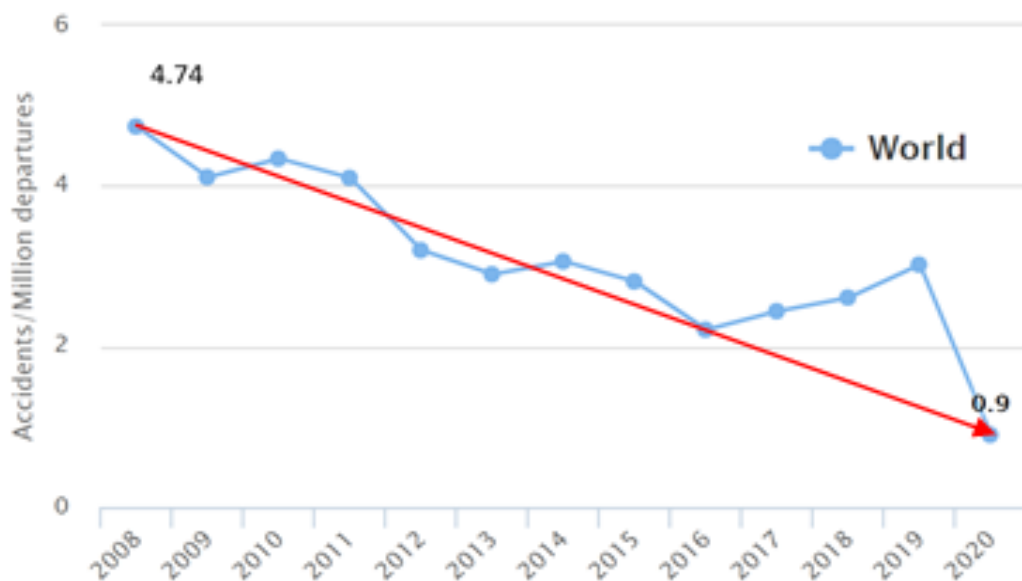


Figure 42: Accident rate in the aerospace sector. Source: (International Civil Aviation Organization, 2021)

The dramatic reduction of the accident rate, depicted from the previous figures, has only been achieved by a long ongoing commitment by the commercial aviation industry to place safety at the heart of its mission. While a significant part of this success is due to advances in the technology, a crucial element has happened within different eras (International Civil Aviation Organization, 2013), where aviation safety has been broadening the safety term and influencing factors, as showed in Figure 43.

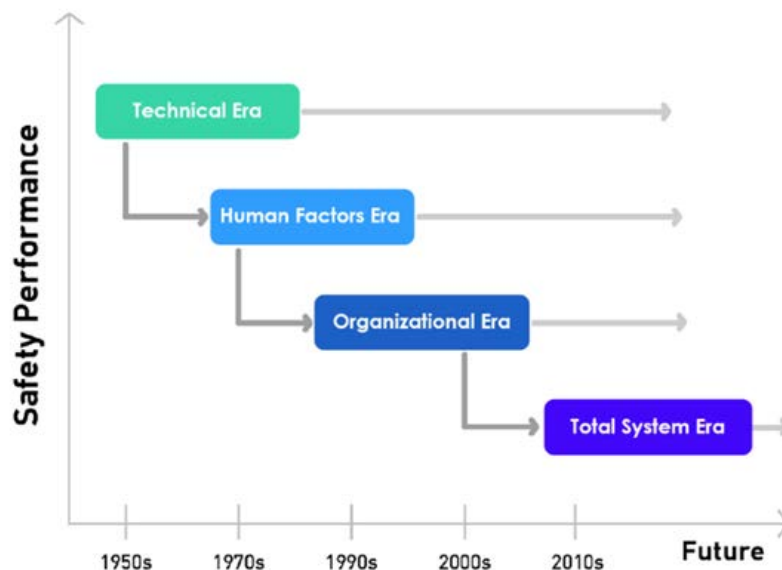


Figure 43: Evolution of safety in the aviation sector. Source: International Civil Aviation Organization

At its early days (Technical Era), when aviation was emerging as a form of mass transport, all the accidents were related to technical or technological failures. The focus of safety endeavours was put towards the investigation and improvement of technical factors, such as the airplane. These improvements led to a decline of fatal accidents and the term safety was broadened to the human factors (Human factors Era), including things like the man/machine interface. Despite the effort in understanding the human factors, today they still are a recurrent source of accidents. During this era, human factors tended to focus on the individual, without considering the operational and organizational side. It was not until the 90s, when safety started to include the organizational culture and policies on effectiveness of safety risk controls (Organizational Era). During this era, the recurring safety data collection and analysis enabled organisations to monitor safety risks, which led to the current safety management approach. As per today (Total System Era), in the 21st century, states and service providers are implementing State Safety Programme (SSP) or (Safety Management Systems (SMS) with a systemic approach, however with minimal regard for the wider context of the total aviation system.

3.6.3.1 International Civil Aviation Organization approach to safety

These eras have been governed by an effective regulation coming from the International Civil Aviation Organisation (ICAO), an outcome of the Chicago convention in 1944. This international

agreement, concerning most of the NATO countries, established the basis of airspace management, aircraft registration, safety and security, sustainability, amongst others. These accepted decisions and procedures are collected in the ICAO Annexes. Annex 19 concerns Safety at a State level and includes the strategy to manage risk at a proactive level, including the four required safety pillars:

- *Safety Policy*: it defines top management objectives and requirements, provides the structure, procedures and controls of the SMS implementation.
- *Safety Risk Management*: design process, where the objectives, systems and environment of the operation are understood to identify the hazards and develop risk controls; hazards are identified, analysed for risk, assessed and controlled.
- *Safety Assurance*: a performance assurance process that monitors and measures risk controls to assure a continuing operational safety.
- *Safety Promotion*: processes necessary to support a sound safety culture (communication and training).

Aside *Annex 19*, ICAO provides *Doc9859: Safety Management Manual*, which is aimed at supporting States implementation of the Safety Management provisions. Safety is defined as the state in which the possibility of harm to persons or property damage is reduced to and maintained at or below, an acceptable level through a continuing process of hazard identification and risk management (International Civil Aviation Organization, 2013)(International Civil Aviation Organization, 2013).

To reduce or maintain risks at an acceptable level, there already exist risk management processes from different aviation authorities that sharing major commonalities, as displayed in Figure 44 (Federal Aviation Administration, 2018) (European Union Aviation Safety Agency, 2019):

- *System analysis*: designed to gain specific information to understand the process to identify hazards and measure performance;
- *Hazard record*: gathering specific information with the *What-if* strategy; it could go wrong with the procedures under typical or abnormal operations that can be considered as hazardous;
- *Risk analysis*: determines the likelihood and the severity of the potential injury or damage and the resulting consequences if the event occurs;
- *Risk assessment*: decision step to determine if the risk is acceptable or not; when severity or likelihood is low, the process might end and be ready for operation, the process moves to the safety assurance and risk level remains acceptable;
- *Risk control*: if the risk is unacceptable, a risk control mitigates it to an acceptable level, returns to the system analysis and performs the entire Safety Risk Management to determine the meeting of those requirements. This loop is continued until the risk is acceptable or until the operation cannot be allowed because the risk is too great.

To identify the risk, each hazard must be analysed for the severity and likelihood of the consequence. Hazard probability and severity Tables 6 and 7 are obtained from (International Civil Aviation Organization, 2013). Additionally, interaction of risks and tradeoffs must be studied using

available tools to optimize efficiency as well as understand interacting systems that may cause failures not obvious during singular FMEA analyses.

Table 6 Hazard probability. Source: Safety Management Manual (International Civil Aviation Organization, 2013)

Probability	Meaning	Value
Frequent	Likely to occur many times.	5
Occasional	Likely to occur sometimes.	4
Remote	Unlikely to occur, but possible.	3
Improbable	Very unlikely to occur.	2
Extremely improbable	Almost inconceivable that the event will occur.	1

Table 7 Hazard severity table. Source: Safety Management Manual (International Civil Aviation Organization, 2013)

Severity of Occurrence	Meaning	Value
Catastrophic	Equipment destroyed. Multiple deaths	A
Hazardous	Major equipment damage. Large reduction of safety margins. Serious injury.	B
Major	Significant reduction in safety margins. Serious incident. Injury of persons.	C
Minor	Nuisance. Operating limitations. Use of emergency procedures.	D
Negligible	Few consequences.	E

3.6.4Space

European space safety is covered by multiple organisms, however, only one have mandates that exclusively focus on space. Anyhow, there is a significant amount of dialog between these organisations to prevent duplication of standards and to create an iterative process (Figure 44). These organisations are: European Commission, Comité Européen de Normalisation (CEN), European Aviation Safety Agency (EASA) and European Cooperation for Space Standardization (ECSS).

The most significant effort for the production of space safety standards in Europe is the ECSS initiative, allowing at the inclusion of important minimum safety standards throughout the European space industry. These vary from project management to engineering and to product assurance. Safety is considered as an element that goes throughout design, manufacturing, launching and mission and the specific focus of ECSS on space safety is documented in the product

assurance document Q 40: Safety (European Cooperation for Space Standardization, 2017). In this document, the safety policy can be found, along with the safety programme and engineering (including safety of human in spaceflight missions, atmospheric re-entry, or safety risk and control). A more detailed document regarding risk management is: *M-80: Risk management* (European Cooperation for Space Standardization, 2008).



Figure 44: Safety Risk Management processes according to (European Union Aviation Safety Agency, 2019) (up) and (Federal Aviation Administration, 2018) (down)

The risk management process proposed by ECSS is a four-step iterative process (Figure 45). Similar to aviation, there is a policy, a risk management process and an assurance process. To assign the risk of each hazard, severity and likelihood must be analysed. Examples are in Table 8, 9 and 10.

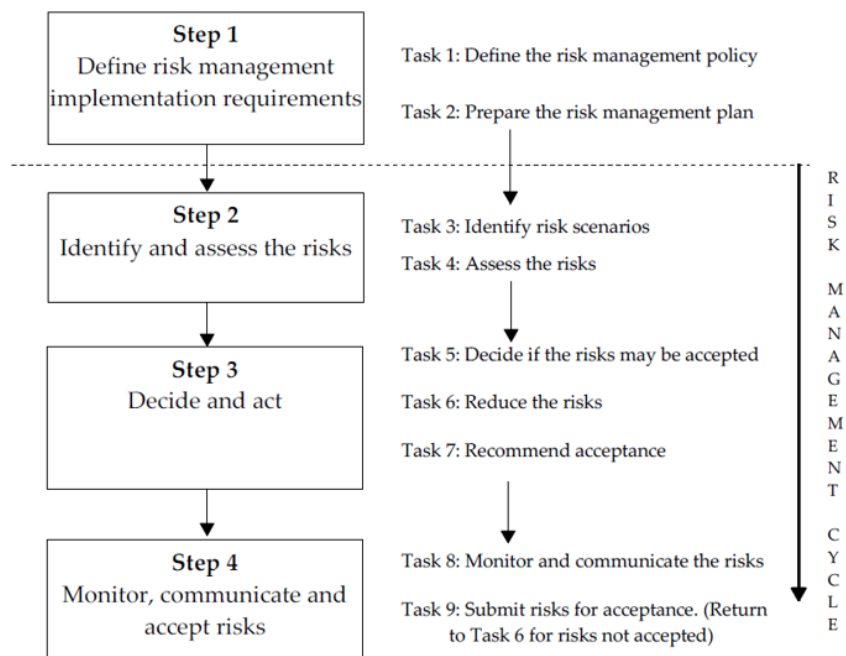
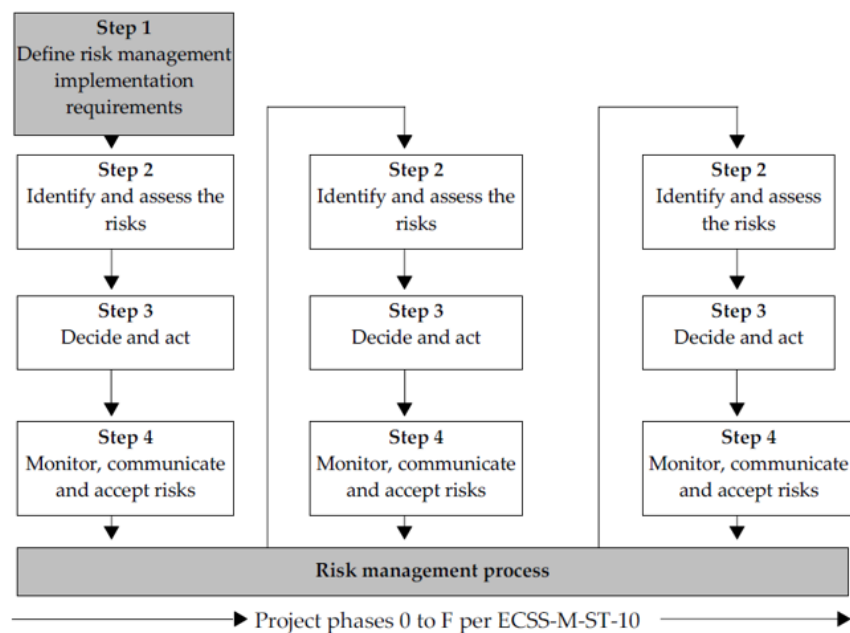


Figure 45: Iterative risk management process (up) and its tasks (down)

Table 8 Example of a likelihood scoring scheme: Source: European Cooperation for Space Standardization

Likelihood	Meaning	Value
Maximum	Certain to occur, will occur on or more times/project	E
High	Will occur frequently, 1/10 times per project	D
Medium	Will occur sometime, 1/100 times per project	C
Low	Will seldom occur, 1/1000 times per project	B
Minimum	Will almost never occur, 1/10000 or more times per projects	A

Table 9 Example of a severity scoring scheme. Source: European Cooperation for Space Standardization

Severity	Meaning: impact on (for example) cost	Value
Catastrophic	Leads to termination of the project	5
Critical	Project cost increase > X%	4
Major	Project cost increase > Y%	3
Significant	Project cost increase > Z%	2
Negligible	Minimal or no impact	1

Table 10 Risk of death in aviation and space

Sector	Risk of death [/100 million passenger x km]
Aviation	0.025 (European Transport Safety Council, 2003)
Space	0.230 (Staples & Redelmeier, 2014)

Compared to aviation, spaceflights operate at much lower volumes (Figure 46) due to their high costs. These costs are derived from the difficulty of operation in such extreme conditions of near vacuum pressures, radiation, communications, power supply, etc. Consequently, the number of fatal accidents is considerably lower than aviation in absolute terms, but when comparing accident rates, spaceflights result on a higher risk of death.

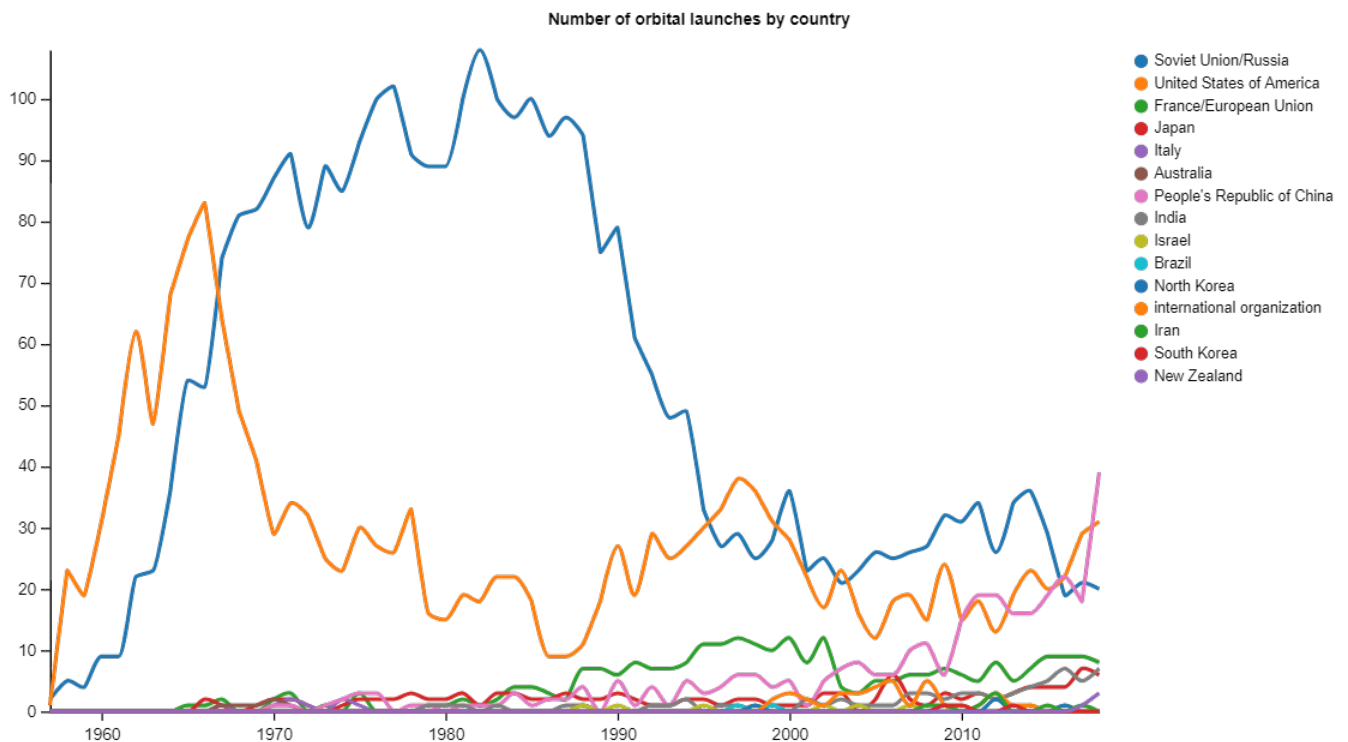


Figure 46: Orbital launches by country

3.6.5 Automotive

The automotive industry is being developed rapidly due to both the electrification of vehicles and the race towards autonomy. These topics are relevant for Hyperloop, together with, e.g., production of cars that will have similarities with the production of vehicles in the future. The ISO 26262:2018 series on functional safety for the automotive domain includes safety case as a requirement but having a safety case is not required by law. In addition, UL issued the standard UL4600:2020 *Standard for Safety for the Evaluation of Autonomous Products*. The Standard uses a claim-based approach that prescribes topics that must be addressed when creating a safety case. It is intended to address changes required from traditional safety practices to accommodate autonomy, such as the lack of human operator(s) to take fault mitigation actions.

Another aspect being studied and implemented by most of the main automotive manufacturers are Agile and DevOps approach due to the need to speed up continuous development of the vehicle after entering the market. Europe's Rail (Shift2Rail successor) discussions sees this strong development as a major competitor to rail. Therefore, both rail and Hyperloop should establish modern development processes too.

A Hyperloop consists of several products and parts. As a result, a Development Interface Agreement (DIA) (ISO 26262-8:2011 chapter 5.5.2+Annex B (informative) example) are relevant for Hyperloop too. This could preferably be adapted to a hyperloop system together with a safety case and a safety manual (IEC 61508). The safety manual shall describe the guaranteed safety properties and the limitations of the product and guide the users in product installation, commissioning, operation and maintenance.

Different approaches to define levels of automation exists for the different domains. The levels have had the most focus as part of the automotive domain. For the Hyperloop domain, this is less problematic due to the *simple* tube. Anyway, it is important to be aware of the difference between automatic and autonomous travel, especially from a certification point of view.

3.6.6 Seaborne

Seaborne transport has an approach that are relevant for Hyperloop: the *Safe Return to Port* principle affecting the SOLAS regulations applicable to new passenger ships having their keel laid on or after 1st July 2010, having a length of 120 m or more or having 3 or more main vertical zones. As per these regulations, a passenger ship shall be designed so that the essential systems remain operational after a fire casualty. which does not exceed casualty threshold, or a flooding of any single watertight compartment and the ship is able to proceed to a safe port under their own power. This may sound simple in theory, but poses a real challenge to ship designers. For hyperloop this means safe travel to a safe haven.

3.6.7 Process industry

A Hyperloop system consists of several pumps and valves. The process industry has been using valves and pumps for many years. They have often been certified according to IEC 61508 and IEC 61511 (system level). Relevant guidance exists, including suggested SIL for the offshore industry NOROG 070 by (Norwegian Oil and Gas Association, 2020). This guideline is developed as a joint industry project between operators, vendors, engineering companies, contractors and consultants. To obtain the required risk reduction, both intrinsic and other types of safety barriers are normally implemented. Details concerning the design and operation of safety-related systems other than intrinsic barriers are not covered by the IEC standards and not included in this guideline. However, performance requirements for non-instrumented systems shall be defined and should be part of an overall barrier strategy. Based on the estimated Probability of Failure on Demand (PFD), the corresponding obtainable SIL requirements are given. These performance requirements are hereafter referred to as minimum SIL in this guideline.

3.7 Studied systems of the Hyperloop

Throughout this section, the potential and common hazards that may exist on the Hyperloop are evaluated. The process of identifying and analyzing risks and hazards is complex and consists of conducting both qualitative and quantitative analysis. Qualitative analysis is necessary to identify and understand risks, which are subsequently analyzed in the quantitative study to determine the probability of occurrence and impact. These two analyzes are crucial for the safety analysis of the hyperloop system. Hyperloop must be studied throughout its entire life cycle to define the risks associated with its construction, commissioning, operation and end of life. During all these stages (Figure 47), different degrees of difficulty and errors may arise. Mis-conceptualization or poor design lead to failures in the different components that affect systems and therefore cause hazards that must be considered, according to EN 50126.

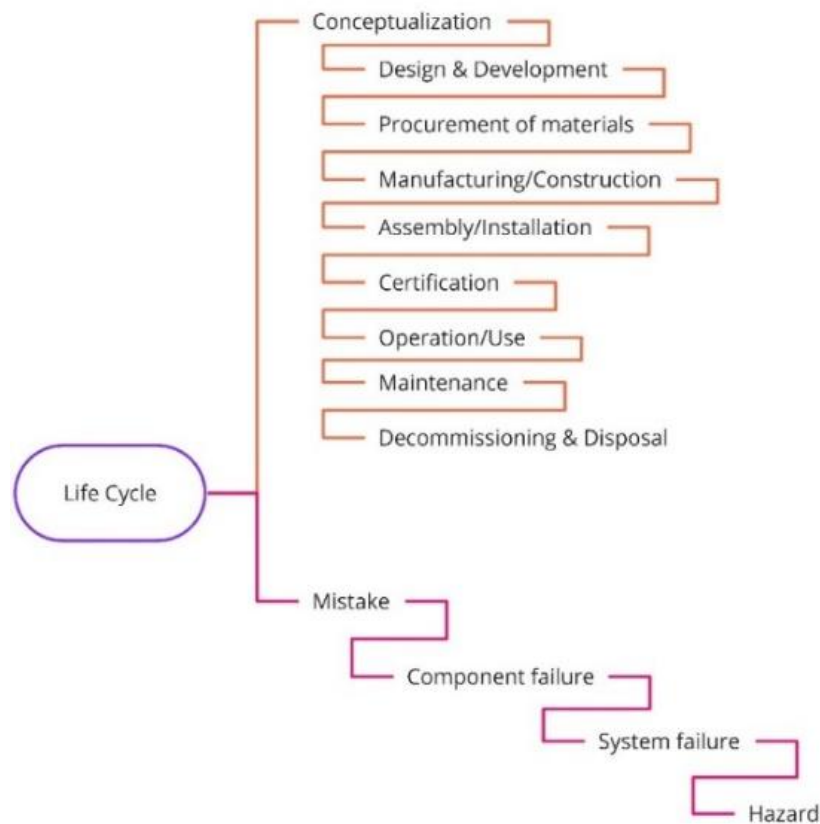


Figure 47: Life cycle and level of failures

For the safety analyses, the common components of Hyperloop solutions have been defined (Delft Hyperloop, 2019) (AECOM, 2020) (Gamero Dalda, 2021) (Jacobi, Oost, Vliem, Van den Brink, 2021) (Prada Lopez, 2021) and summarized in Table 11.

The combination of failures in the different subsystems can be studied depending on their frequency, the severity of their consequence and the possibility of their detection (Figure 48).

Table 11 Definition of the different systems of Hyperloop

System	Definition
Propulsion and Braking (longitudinal), Levitation (vertical) and Guidance (lateral)	This system is one of the most important of the Hyperloop, since it is responsible for generating the movement (Propulsion and Braking) and levitate the vehicle on the track (Levitation). The guidance system is responsible for controlling the route that the vehicle follows through the infrastructure
Power Supply	This system is responsible for supplying the necessary electrical energy to the equipment so that they can carry out their work
Communications	The communication system is responsible for transmitting orders and needs of each system, making everything operating in a synchronized way and in due time. This system is vital for security as it is necessary for the personnel to have all the information they need to be able to function properly. It also includes data management and processing, system hack, location sensors, monitoring system and interfaces

System	Definition
Control and command	The control-command system is responsible for controlling the actions of the other systems, such as propulsion and brakes, giving them the right orders at the right time
Vehicle	The hyperloop system, which includes the cabin where people and goods are transported. The capsule includes batteries, facilities as oxygen, air conditioning, seats, entertainments and other comfort conditions, such as temperature or noise
Infrastructure	Infrastructure subsystem referees to tunnel, tube, pylons, track and the needed equipment to keep the vacuum (pumps and valves)
Terminal and stations	In the station, passengers or goods begin or end their journey. In this establishment the vehicles leave and arrive, so it will be composed, at least, of a platform for passenger boarding and alighting
Signalling	The signalling is part of the control and communications system. In particular, the signalling system encompasses all signals related to vehicle and pathway positions

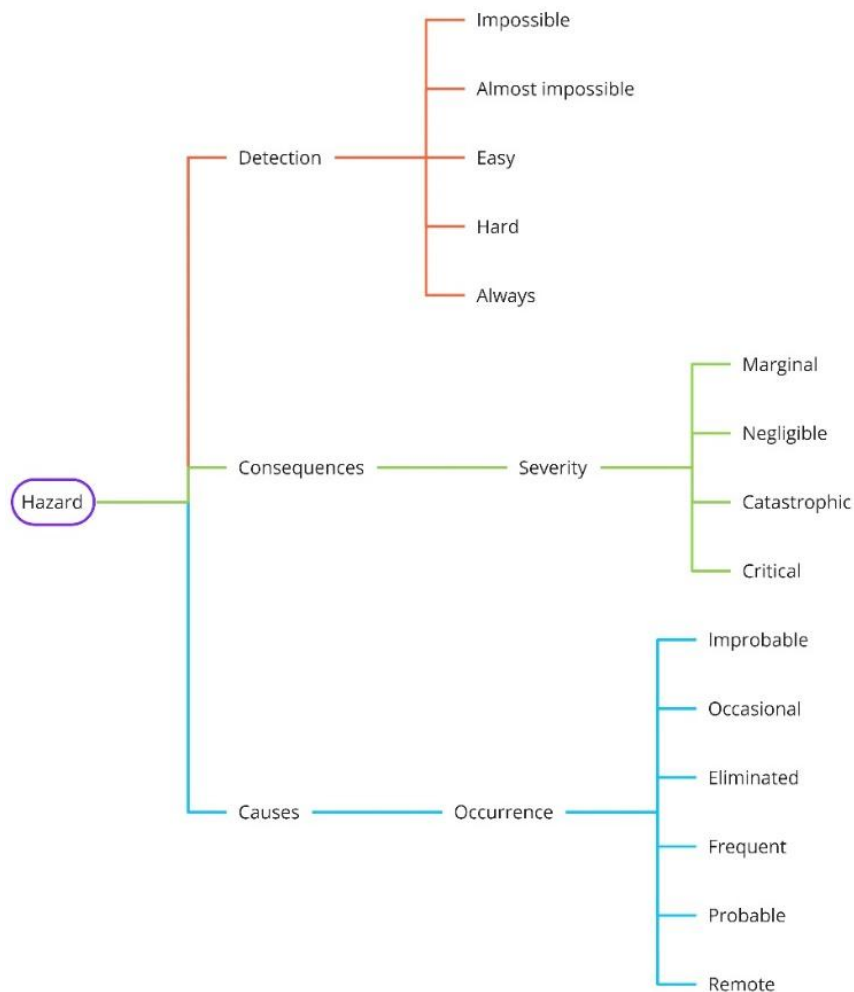


Figure 48: Combination of failures and its classification

The severity level has been based on how much it affects people and the operation of the system. All risks that involve serious damage or death of people are automatically classified as critical or catastrophic. In the classification of severity levels, among other criteria, bands of monetary amounts of costs derived from human damages have been used. To carry out this quantification, the compensation corresponding to victims of medical negligence in 2020 has been used as a basis.

Table 12 provides with a description of the severity classified in five levels from 1 (Catastrophic) to 5 (Negligible). Differently, Table 13 establishes five levels of the failure detection frequency from A (Frequent) to E (Improbable).

Table 12 Severity description

Description	Severity	Result Criteria
Catastrophic	1	Operating conditions are such that human error, environment, design deficiencies, element, subsystem or component failures or procedural deficiencies may cause death or major system loss, thereby requiring immediate cessation of the unsafe activity or operation. The negative consequences are such that may cause the entire organization to fail or can severely impact on daily operations or monetary loss \geq 60 million EUR
Critical	2	Operating conditions are such that human error, environment, design deficiencies, element, subsystem or component failure or procedural deficiencies may cause severe injury, illness, or major system damage thereby requiring immediate corrective action. The negative consequences will impact on the organization's success or on its objectives or monetary loss in the range 10-60 million EUR
Moderate	3	Operations conditions may cause moderate injury, illness or negative consequences bringing moderate hazards for the organization and their goals, not affecting the success of the system/organization or monetary loss in the range 1-10 million EUR
Marginal	4	Operating conditions may commonly cause minor injury or illness or minor systems damage such that human error, environment, design deficiencies, subsystem or component failure or procedural deficiencies can be counteracted or controlled without severe injury, illness or major system damage or monetary loss in the range 0.5-1 million EUR
Negligible	5	Operating conditions are such that personnel error, environment, design deficiencies, subsystem or component failure or procedural deficiencies will result in no, or less than minor, illness, injury or system damage. Risks that do not have real negative consequences or do not suppose a significant threat or monetary loss <0.5 million EUR

Table 13 Level of frequency of hazards

Description	Level	Definition (specific Individual Item)
Frequent	A	Likely to occur often in the life of an item
Probable	B	Will occur several times in the life of an item
Occasional	C	Likely to occur sometime in the life of an item
Remote	D	Unlikely, but possible occurrence in the life of an item
Improbable	E	So unlikely it can be assumed occurrence may not be experienced

Finally, a hazard matrix (Table 14) combines frequency and severity with a colour code.

Green area: These risks are deemed acceptable. The consequences of the risk are minor and unlikely to occur. These types of risk are generally ignored. Risks are acceptable due to their low severity. *Acceptable Risks.*

Yellow area: It is very possible that something will happen, but these risks have consequences a little more serious than the green ones; even so, they are *minor* risks. If possible, take steps to prevent medium risks from occurring, but they have not a high priority and should not significantly affect the success of the organization or project. Information should be provided, or technical measures can be taken. *Tolerable Risks.*

Orange area: Serious risks that have significant consequences and are likely to occur. Prioritizing and responding to these short-term risks is important. Changes must be made in design. *Unacceptable risks.*

Red area: Catastrophic risks that have serious consequences and are very likely to occur. These risks are the highest priority. It must be answered immediately, as they can threaten the success of the organization or its particular objectives. Must always be avoided. *Unacceptable risks.*

Table 14 Level of risks matrix

Likelihood	Severity				
	Negligible (5)	Marginal (4)	Moderate (3)	Critical (2)	Catastrophic (1)
Frequent (A)	A5	A4	A3	A2	A1
Probable (B)	B5	B4	B3	B2	B1
Occasional (C)	C5	C4	C3	C2	C1
Remote (D)	D5	D4	D3	D2	D1
Improbable (E)	E5	E4	E3	E2	E1

3.8 Hazard log

The hazard log (also named hazard record) lists and tracks all hazards, hazard analysis results, risk assessments, and risk reduction activities during the whole lifetime of a safety related system. A complete hazard log is normally one of the top five references in a safety case. The hazard log approach enables the manufacturer to have a complete overview of all relevant hazards.

The benefits of using a hazard log are that:

- It is one of the main references in the safety case. A safety case is required by, e.g., EN 50129:2018 (railway), ISO 26262:2018 (automotive), and UL4600:2020 (automotive)
- The European railway regulation for "the common safety method for risk evaluation and assessment" (402/2013 and EU 2015/1136) requires a hazard log (hazard record) to be created.
- It presents an overview of the hazards and, e.g., the relevant responsibility and mitigations.

EN 50126-1:2017 and EN 50129:2018 define a Hazard Log as "document in which hazards identified, decisions made, solutions adopted, and their implementation status are recorded or referenced.

The hazard log below has included the results from using a hazard matrix as described in chapter 2.7 "Studied systems of the Hyperloop".

3.9 Guidance System Analysis

The guidance system is responsible for controlling the route that the vehicle follows through the infrastructure. The main part of this system is formed by the route that the vehicle must follow and the switches, which allow modifying the route that the vehicle follows through the infrastructure.

The presence of these switches is necessary in order to reduce costs, since it would be excessively expensive to build the infrastructure that connects only two points. These deviations allow you to interconnect different starting points and destinations making the system more efficient. The possible use of two types of switches in the Hyperloop has been taken into account. The first type would be the high-speed switches, which would employ the active lateral guidance system to exert the necessary force on the vehicle to produce the changing of the track, as described in HYPERNEX D2.1. The second type would be conventional track switches, mechanical only, as those used in Maglev trains, not prepared for a change of track at the Hyperloop speed, usable only after a relevant speed reduction of the vehicle.

The possible dangers that can affect the guidance system have been divided into the main subsystems that compose it: the lateral active guidance, the conventional switch and the track, in addition to possible human errors.

3.9.1 Active lateral guidance

The active lateral guidance is responsible for creating the necessary forces in the high-speed switch to produce the change of track properly, in addition to keeping the vehicle stable for the rest of the route. The most critical moment is when it is necessary to generate greater force for the switch. Within this subsystem, three main possible failure modes have been defined.

H1: Communication failure. An error may occur in the communication between the control center and the guidance system. This could cause the lateral active guidance to be activated late. This failure could cause the vehicle to collide with the infrastructure as it does not have enough time to make the layover. The level of consequence that has been assigned to this failure is critical, as a high-speed crash would damage the vehicle and passengers inside. The probability of occurrence is assigned occasional, as it is possible for the communication system to fail. This failure is thus at level C1 within the risk matrix and it is necessary to apply mitigation measures. The main mitigation measure for this failure would be to have a backup communication system that allows the order to be sent on time if another fails. It is important to constantly monitor the status of communications, so if it fails to have reaction time to act. If these measures are applied, the risk

would be reduced to the C4 level, in the yellow area of the matrix since the consequences of this failure would be reduced.

H2: Power outage. The active lateral guidance would not be put into operation, which would make the vehicle unable to change track and, in the worst case, it could collide with another vehicle that is on the track that has been invaded by the vehicle that has not been able to change it. Therefore, the level of the consequences of this failure is moderate, and the probability of occurrence is remote, so the level presented in the risk matrix is D2, being located in the orange zone and thus needing to apply mitigation measures. The most effective mitigation measure for this case will be to have a secondary power supply that would allow the change of tracks, as well as that the vehicles maintain a safe distance in the switches until there are no more vehicles pending to pass. Thus the consequences of this failure would be reduced to the degree of marginal, since it would only be that the vehicle deviates from its course and must correct it, finally being located this threat in the green area of the matrix, D4.

H3: Magnets deterioration. It is possible that over time the magnets will deteriorate and lose the characteristics they had at the beginning, until a point where they are not able to generate the necessary force to perform the track change. This could cause a collision between the vehicle and the tunnel by failing to change lane completely. Therefore, the consequences of this failure have a critical level, but the occurrence of this is remote. This fault is located in the orange zone, D2, of the risk matrix. To avoid this it is important to monitor the operation of the magnets to detect possible signs of wear and perform a maintenance plan, both predictive and corrective, suitable so that the magnets are in the best possible condition. With this, the level of occurrence of this threat would be reduced until it is almost unlikely to occur, passing the threat to an E2 level, in the yellow zone of the matrix.

3.9.2 Conventional route change

As the high-speed track change system is not yet fully tested, the possibility of using low-speed mechanical track switch, such as those used in magnetic levitation trains is also being considered, with the possible failures below.

H4: Communication failure. Failing of communication between the control center and the bypass could result in a situation where the bypass is triggered late or not. This failure could cause the vehicle to collide with the infrastructure as it does not have enough time to make the layover. The level of consequence that has been assigned to this failure is very critical, as a high-speed crash would damage the vehicle and the passengers inside. The assigned probability of occurrence is occasional. This failure is thus at level C1 within the risk matrix and it is necessary to apply mitigation measures. The main mitigation measure for this failure would be to have a backup communication system that allows the order to be sent on time if another fails. It is important to constantly monitor the status of communications, so if it fails to have reaction time to act. If these measures are applied, the risk would be reduced to the C4 level, in the yellow area of the matrix since the consequences of this failure would be reduced.

H5: Power outage. The switch would not be put into operation, which would make the vehicle unable to change track and, in the worst case, it could collide with another vehicle. Therefore, the level of the consequences of this failure is moderate, and the probability of occurrence is remote, so the level presented in the risk matrix is D3, being located in the orange zone and thus needing to apply mitigation measures. The most effective mitigation measure would be to have a secondary power supply that would allow the change of roads to be carried out. In addition, this must be ensured that the vehicles maintain a sufficient safe distance from a switch so that in case a vehicle cannot change track, the time is enough to stop both the vehicles. Thus the consequences of this failure would be recovered to the degree of marginal, finally being located this threat in the green zone of the matrix, D4.

3.9.3Track

The track is responsible for guiding the vehicle through the infrastructure. The main failure to take into account is the following.

H6: Track misalignment. It is necessary that the alignment of the track is permanent to prevent any problem to keep the route. Nevertheless, should a misalignment occur, either due to a crash or due to inadequate maintenance, it would cause the vehicle to collide with the track and could damage it, leaving passengers exposed to the vacuum environment inside the tube, which could cause damage. The main mitigation measure is to perform an adequate maintenance of the tracks and to monitor their condition to be able to detect possible failures.

3.9.4Human failures

It is necessary to take into account the impact that human actions can have on the guidance system, as it can be a major cause of risks. They are described below.

H7: Lack of maintenance or inadequate maintenance. This could cause systems to malfunction. Therefore, there is a possibility that the change of track will not be activated when vehicle arrives, which could cause the vehicle to collide with the tube or with another vehicle. If the maintenance of the track is inadequate this could have defects such as misalignments or potholes that could cause the vehicle to collide with the track. These damages are not usually very sudden, so the crash would not be very serious. These exposed consequences are quite critical as they could lead to people being harmed in the event of a major collision. The probability of this happening can become occasional, level C, if the necessary precautions are not taken. The level of this risk in the matrix is then C1. To mitigate the risk the main thing would be to ensure that the maintenance plan to be followed is the right one to keep the system in correct condition, in addition the personnel in charge of carrying it out must have the necessary training and the correct physical and psychological capacities. In addition, in the case of switches, it must be ensured that the vehicles of the tracks that approach the switch will be at a sufficient distance, to be able to brake in case the switch does not work and another vehicle invades your track, until this vehicle has passed. Another measure is that switches cannot be activated if a vehicle heading towards them is close enough that it cannot make the complete lading change. With these measures, the chances

of it occurring are reduced to level D, since being a human error will always exist the possibility, and the consequences could be reduced to level 4. Leaving this threat at level D4.

H8: Error triggering a Route. A control room operator accidentally or mistakenly triggers a lane change that should not be activated, either a high-speed or a conventional one. If a vehicle passes through that switch at the time of the erroneous activation, there could be a situation where the vehicle crashes into the tunnel if it cannot make the change of track in time or if it collides with another vehicle heading in the opposite direction or standing on the track that has invaded the vehicle that has suffered the switch. Another possibility is that the vehicle made the change of track without colliding with anything, but its path would be modified. The level of probability of occurrence of this failure has been estimated in remote, level D, but the consequences that can entail if they can be catastrophic in the event of a collision, so it has been assigned a level 1. This threat is therefore located in the red zone of the matrix, level D1. The main mitigation measure is that the responsible for carrying out the tasks of control and command must have the necessary training, in addition to adequate physical and psychological capacities. To avoid collisions, it would be best if the guidance system in charge of controlling the switches did not allow the activation of the track changes if there is a vehicle close enough to that switch to be able to reach it before it finishes making the track change, thus avoiding that in case of accidental activation the vehicle crashes into the tube because it has not given time to change. Collision between two vehicles can be avoided if the distance between the vehicle standing or driving on its road properly and the switch is large enough for the two vehicles to brake before colliding. This distance is a function of the speed at which the vehicles circulate in each area and must be highly controlled and it may be necessary to decelerate or even stop the vehicle to maintain it. Finally, if there is no collision the vehicle will have deviated from its course, so it will be necessary to inform the other vehicles and look for an alternative route or an area to be able to change direction safely and return to the original course. With these measures the level of this threat can be reduced to E3, moving to the yellow zone of the matrix.

3.9.5 Propulsion and Levitation system analysis

This subsystem is one of the most important of the Hyperloop, since it is responsible for generating the movement and levitate the vehicle on the track. The main component in charge of generating the movement will be a LSM or an axial compressor, depending on the Hyperloop solution and for braking it will be a LSM too. The levitation system to be used is very similar to that used on Maglev trains. The possible risks associated with this system are listed and explained in the following points.

3.9.5.1 Linear synchronous motor

The LSM is responsible for propelling the vehicle along the track. The following related risks have been detected.

H9: Acceleration failure. There may be an electrical or mechanical failure in the engine that prevents the vehicle from reaching the speed required to join the track flow. This could cause a collision between two vehicles due to the difference in speed, causing damage to the vehicles and

the people inside, but as the difference in speed will not be too large it will not be a critical error. The consequences of this risk have been classified as moderate, level 3, and its probability as occasional, level D, so this threat would be located in the orange zone of the risk matrix, D3, needing to apply mitigation measures. The main mitigation measure would be to perform a correct maintenance of the LSM and monitor its operation in order to anticipate and avoid possible failures. In case it happens, the nearby vehicles should be warned to reduce the speed immediately and thus avoid a crash. With these measures the risk would be reduced to a D4 level, moving to the green area of the matrix.

H10: Power outage. If the LSM stops receiving energy, the vehicle will begin to decelerate until it stops, being able to collide with another vehicle coming faster from behind, but the difference in speed would not be too great since being the resistance with minimal air and with the non-existent ground takes a long time to brake. Therefore, as in the previous case, the risk level assigned has been D3, having to apply mitigation measures. To avoid this, it is advisable to have a secondary power supply system or a secondary propulsion system, in order to avoid deceleration. It is also important to alert the other vehicles of the fault. If this is applied the risk level drops to D5, remaining in the green zone of the risk matrix

H11: Overhead. An overload in the power that the LSM receives can damage it causing it to not work properly, thus reducing the speed of the vehicle. The probability of this occurring has been taken as occasional, due to fluctuations in energy sources and the consequences would be moderate, as explained in the previous cases. Being the level of this risk C3, in the orange zone of the matrix. In the design of the LSM these possible peaks and drops in the power must be taken into account, so the engine must be able to withstand them and have the appropriate protections. In case it occurs, the other vehicles must be informed so that they reduce the speed. This would reduce the risk level to E4.

H12: Communication failure. The failure of the communication between the control system and the LSM would cause the LSM not to propel the vehicle properly, causing the speed to be higher or lower than it should be. This could lead to collisions with other vehicles with unpredictable speed. The level of consequences associated with this threat is considered critical, level 2, and the probability of it occurring occasionally, level C, so this threat would be located in the red zone of the matrix, level C2. An important measure is that the communication system must be in good condition, being monitored and complying with an adequate maintenance plan. In the event of a failure, it would be important to have a secondary communication system to be able to transmit the orders to the LSM. Applying these measures would reduce the level of risk to E3 in the risk matrix.

3.9.5.2 Magnetic levitation

This is the system that is used to levitate the vehicle on the track, thus making there is no friction between the two. The risks identified for this system are mainly here below.

H13: vehicle too heavy. If the weight of the vehicle is too large, the levitation system will not be able to levitate it at a sufficient distance from the ground, caused possible collisions between the

vehicle and the track. That this will happen is quite unlikely since the levitation system has to be specifically designed to lift the weight of the vehicle, including all systems, such as batteries and the passengers or goods. Because of this, the probability of occurring has been taken as unlikely, level E, and the consequences as moderate, level 3. This threat is located in the yellow zone of the risk matrix, E3, and it is not necessary to take into account mitigation measures.

H14: Magnet wear. It is possible that the magnets lose characteristics and are no longer able to generate the same force as at the beginning. This can cause the space between the vehicle and the track to shrink until a collision occurs. The level of consequences that has been assigned to this risk is 4, since the blow failure does not occur and it can be easily detected when this is happening since the distance between the vehicle and the track is something that must be monitored. Then you can see if it starts to descend, so you can put a solution before it is no longer able to lift the vehicle. The assigned occurrence has been remote, as these magnets take a long time to wear out. So the level of this threat is D4, being already in the green zone and not being necessary to apply mitigation measures.

H15: Misalignment of the levitation system. It is possible either due to a crash or due to inadequate maintenance. This could cause the vehicle to collide with the track, leaving it damaged. The level of consequences of this risk that has been taken is 2, since if the shock could damage the vehicle leaving people exposed to the environment inside the tube and the probability of it occurring is remote, level D. Being this risk in the orange zone, D2, and being necessary to apply mitigation measures.

The main mitigation measure is to perform an adequate maintenance of the levitation system and to monitor its condition to be able to detect possible failures. This would cause the risk to move to the green zone, level E4.

3.9.5.3 Braking System

The braking system is responsible for reducing the speed of the vehicle when necessary. To brake the vehicle you can e.g., use the same LSM used for the acceleration. This system is extremely important because considering the high speed at which the Hyperloop circulates, it is necessary that the braking is able to stop the vehicle in a short time to avoid damage. The detected risks related to braking are below.

H16: Power outage. A failure in the power supply of the braking system could cause the collision between two vehicles or with a vehicle and the tunnel, if it reaches a switch too fast or if the front vehicle slows down, but the following one is not able to do the same. Therefore, the consequences of a failure in the feeding of this system can be quite serious, since there could be people injured in the crash, assigning it level 1. The probability of this happening is quite low, with a level D. Leaving this threat in the red zone of the matrix, D1. The mitigation measures necessary to reduce the level of this threat are to implement a secondary power system that is activated in case of failure of the main one and to have an alternative emergency braking system that works isolated from the other, with an independent power supply. If these measures are applied, the level of the consequences of this threat can be reduced to D4, in the green area of the matrix.

H17: Communication failure. Communication between the control system and the LSM may fail, which would cause the LSM not to brake or even brake late or earlier than it should. That you brake earlier would not pose a very great risk in most cases, but not braking or doing it late could lead to collisions with other vehicles or with the tube if you are not able to reduce the speed enough when you reach a switch. The level of consequences associated with this risk is considered very serious, level 1, and the probability of it occurring occasionally, level C, so this threat would be located in the red zone of the matrix, level C1. An important mitigation measure is that the communication system must be kept in good condition, being monitored and complying with an adequate maintenance plan. In addition to this you should not depend on a single communication system and you should have a backup system to use in case of emergency. Having a secondary emergency braking system is also necessary to avoid this risk. It must have a constant monitoring of the state of brakes, in order to be able to determine in time if a failure of these characteristics occurs. If these measures are applied the level of the risk would be reduced to E4 in the risk matrix. Since it is very unlikely to happen with a secondary communication system and having a second emergency brake you can quickly resort to it to reduce the delay in braking.

H18: Insufficient braking force. There may be a situation where the brake is activated, but it is not able to generate enough force to stop the vehicle as quickly as necessary. This may be due to a possible electrical or mechanical failure of the LSM, which prevents it from applying the full braking force. The consequences of this may be that the vehicle entered the stations with too high speed by colliding with slower vehicle or with the tube in a switch because it could not reduce the speed in due time. The consequences of this type of failure can become very serious if a collision occurs, since it is likely that being the speed so high there will be injuries, so it has been assigned a level 1. The probability of this happening is occasional, as it is a system that is not yet fully developed. Being the level of this threat C1, in the red zone of the matrix. To reduce the impact of this threat, the best option is again the implementation of a secondary braking system, capable of coming into operation quickly in case the main one fails. To prevent it from happening, you must apply a strict maintenance plan to keep it in the right condition and a monitoring activity aimed at the detection of possible signs of failure. After applying these measures, the level of this threat in the risk matrix would pass to the green zone, D4.

H19: Error setting braking curve. The braking system must be able to generate an appropriate braking curve depending on the circumstances. The system may not be able to define this curve due to a software failure or because it does not receive the appropriate information due to a failure in the communication system. The consequences of this risk are that the vehicle could collide with another vehicle or with the tube, if it is not able to brake in time, and injuries could occur in the crash. The degree of consequences is therefore very serious, as people can be harmed in the collision. The likelihood of this occurring is occasional if appropriate considerations have not been taken into account. Therefore, the level of this threat is C1. The main mitigation measures for this case would be that the signalling system information received by the vehicle is sufficient to determine an appropriate braking curve. A redundant communication system between the track and the vehicle is a good option to ensure that the necessary information will be received. It is necessary that the braking system has passed the operating tests that verify that it is able to

function properly. Moreover, an emergency braking action can be applied in case of failure of both communication systems or one of the safety-critical pod components (e.g. brake). The level of risk when applying these measures would be reduced to E2, passing to the yellow area of the matrix.

3.9.5.4 Human failures

It is necessary to take into account the impact that human actions can have on the propulsion and levitation system, as it can be a major cause of risks. The main ones related to this are below.

H20: Lack of maintenance or inadequate maintenance. It is possible that the maintenance of engine, brakes and levitation system has not been performed or that it has been done incorrectly. This could cause systems to malfunction. Therefore, there is the possibility that the system is not able to brake properly, which is the biggest risks since a crash at such a high speed can be fatal, to accelerate, or collide with the track when the levitation system fails. These exposed consequences are quite critical as they could lead to people being harmed in the event of a major collision. The probability of this happening can become occasional, level C, if the necessary precautions are not taken. The level of this risk in the matrix is then C1. To mitigate this risk, it would be necessary to ensure that the maintenance plan is able to keep the system in correct condition and that the personnel in charge of carrying it out has the necessary training and the correct physical and psychological capacities. In addition to having an emergency brake and a secondary propulsion system. The levitation system must also automatically deploy the wheels whenever the distance between the vehicle and the track is reduced too much. With these measures, the chances of it occurring are reduced to level D, since being a human error will always exist the possibility, and the consequences could be reduced to level 4, leaving this threat at level D4.

H21: Erroneous activation of the braking system. It is possible that its causes an accidental activation of the vehicle braking system by an error of a control room operator or the driver, in case the vehicle has it. If this happens the vehicle would reduce its speed and could collide with a following vehicle that circulates at normal speed. The probability of this failure is remote, level D, and the consequences can become moderate, level 3, if the collision occurs. Being its level in the risk matrix D3. As in the case of the previous threat, when it is a human error, the best measure is to ensure that the people in charge of the control of the vehicle have the appropriate training and are in the correct mental and physical conditions to carry out their work. Another way to avoid this is by the communication system between vehicles, which inform vehicle on the speed and position of the vehicle in front of them and adjust their braking curve correspondingly, thus preventing the collision. Therefore, it must be ensured that this system works correctly, by monitoring its condition and an appropriate maintenance. With these measures, the level of risk of this threat could be reduced by moving to the green zone, level E5.

H22: Erroneous activation of the propulsion system. The propulsion system can be activated incorrectly, due to a failure of the control center operators or an error of the driver in the vehicle, if any. This failure could cause the vehicle to accelerate too much when it reaches a switch, which could cause a collision with the tunnel or another vehicle in front. The consequences of this error are critical, level 2, and the occurrence is D-level, remote. Therefore, the level it happens to occupy in the array is D2. As with all other risks due to human error, the primary mitigation measure must

be to ensure that the personnel in charge of these operations have the necessary capabilities and are in the right condition. To avoid collisions between vehicles it is important that the communication system between them work correctly so that the system can define the necessary braking curve depending on how the adjacent vehicles circulate. To avoid entering dangerous points, such as switches or stations, too fast, it would be advisable for the system to set a maximum vehicle speed depending on which area you are in. If the vehicle approaches a switch that the beacons warn, the system should limit the maximum speed at which it can circulate automatically, avoiding possible accelerations. If these measures were taken into account, the level of risk in the matrix would be reduced to E4, in the green zone.

3.10 Power Supply Analysis

This subsystem is responsible for supplying the necessary electrical energy to the other equipment so that they can carry out their work, so this is one of the most important and critical. The different risks have been divided according to the components of this system.

3.10.1 External power supply

This point deals with the possible risks related to the energy obtained from the national grid, since this can also have failures. The two main risks are temporary spikes or falls in supply and a total power outage. Both dangers may be due to instability or failures of the network from which the energy is obtained or to its sabotage.

H23: Power outage. It would cause all systems to stop working, as they all need power. Therefore, this risk is quite critical, as it could cause a strong collision between the vehicle and the track, leaving it damaged, so it has been assigned a severity of 2. Even so the chances of this happening are low, so the occurrence will be D. This threat is located in the orange zone of the matrix, D2, being necessary to apply mitigation measures. To prevent all systems from failing, a serious mitigation measure would install redundant power supplies for the main systems, both in the vehicle and in the infrastructure, that would allow the vehicle to continue circulating until it reaches a safe area from which occupants can be evacuated. With this measure, it is estimated that the occurrence could be reduced to the E2 level, remaining in the yellow zone of the matrix.

H24: Small spikes or drops in supply. The power supply may not be constant due to grid fluctuations. The chance of small spikes or drops in supply is greater than that of a total outage, probability C, and the main consequences of this is that some systems can be damaged if they are very sensitive or the peaks very large, so the severity will be 3. This threat is located in the orange zone C3 of the matrix, needing to apply mitigation measures. The best mitigation measure for this case is that all the different systems have protection measures against voltage rises or falls, in order to prevent them from being damaged. With this, it is estimated that the occurrence and severity of the threat is D4 level in the green zone of the matrix.

3.10.2 Auxiliary power supply

This point indicates the risks related to the auxiliary power supply. This source will be in charge of feeding the equipment in case the main source fails. In this case it will not be a connection to the national grid, but rather external batteries or generators will be used.

H25: Power supply auxiliary system failure. The main risk of this source is that, when it is necessary to resort to it, it does not work, either due to a bad connection or a bad state of it, being the consequences quite serious, it is assigned a level 2. However, the probability of this happening is low, level D. Being this risk located in the orange zone of the matrix, with a level D2, it is necessary to apply mitigation measures. To reduce this risk it is advisable to carry out periodic reviews of the condition of the auxiliary power supply to verify its correct functioning, and to carry out the relevant maintenance to ensure its optimal conditions. This reduces the level of occurrence of this threat to E2, passing to the yellow area of the matrix.

3.10.3 Solar panels

The solar panels will be installed at the top of the tube and will work in parallel to the main power system by supplying a quantity of energy depending on local and hourly meteo conditions.

H26: Solar panel failure. The main risk of this subsystem is that the panels do not work properly due to lack of maintenance or external causes, such as an impacting object that damages them. The probability of this event is high, as it can occur several times during its lifetime (level B of occurrence). The consequences are not very important because this is a secondary system and the Hyperloop must be prepared to operate without the energy coming from the panels because it must also be able to operate at night, so it is assigned a level 4. This risk is located in the yellow zone of the matrix, B4, and mitigation measures are not necessary.

3.10.4 Power transmission system

This system will be responsible for the transmission of the electricity from the sources to the different equipment. The main transmission system will be through cables, so these are a critical point when it comes to the proper functioning of the systems. The possible consequences of major systems failing due to lack of power have also been analyzed. The detected risks for this case are below.

H27: Induction loop. It would be the system in charge of transmitting the electrical energy to the vehicle if you do not opt for feeding it by batteries only. If this system fails, it could stop receiving power and all its systems would stop working. This risk should affect all vehicles in the area where the induction loop failed. This would cause the levitation system to stop working, collide with the track and damage the vehicle, leaving passengers exposed to the environment inside the tunnel. Therefore, the consequences of this risk are severe, level 2, and the probability of this happening is low, level D. This places this threat at level D2, in the orange zone. The main mitigation measure to avoid the consequences of this threat would be to have small batteries inside the vehicle that allow the vehicle to continue to circulate until it reaches a safe area. It is also important that, in

case the levitation system fails, the wheels are automatically deployed to avoid collision with the track. The level in the risk matrix becomes D4.

H28: Damaged cables. If the cables are not in optimal condition, the energy may not be properly transmitted to the equipment. These cables can be damaged because they are not protected or because proper maintenance has not been performed. If the cables do not feed the equipment correctly, they can fail, which depending on the equipment can cause the vehicle to collide with the track (Levitation System) or with another vehicle (Communication or Braking System). Being the consequences of level 1 as they can cause very serious damage to both the vehicle and people if the systems fail. The probability of this still occurring is low, so it is assigned a level D. Leave this risk at level D1 of the matrix, needing mitigation measures. To prevent this from happening, it is necessary to carry out an adequate maintenance plan, with which all cables are kept in the right conditions, in addition the equipment must be monitored to detect possible failures as soon as possible. Thus, reducing the level of this threat to the yellow zone E3.

H29: Exposed cables. They are dangerous if people can access to them and, due to the high voltage, they can be damaged, which is a rather serious consequence, level 1. In addition to that, they are more susceptible to damage or sabotage. Still, the probability of this happening is relatively low, assigning it a level D. Therefore, this threat remains in the red zone of the matrix with a level D1, which is necessary to apply mitigation measures. In the design phase, cables should not be located in areas easily accessible to the public, in addition to the same as in the previous case, perform a correct maintenance of the cables to check their condition. It is also necessary to install the appropriate protections so that in the event of unwanted contacts the protection are activated. This reduces the level of this threat to E4, moving to the green area of the matrix.

H30: Levitation system. If it stops receiving the energy necessary to operate, it could leave the vehicle colliding with the track and the tunnel, which is a very serious risk, since it can cause relevant damages to vehicle and people onboard. Being the level of the consequences associated with this risk of 1, although the probabilities of this occurring are low, level D. Leaving this threat in the red zone of the matrix, at level D1. It is therefore necessary to implement mitigation measures for this threat. The first mitigation measure would be that in case the distance between the vehicle and the track is reduced too much, the vehicle wheels are automatically deployed to avoid collision. It is also important to have a secondary power supply system that allows the vehicle to circulate until it reaches a safe state. This would reduce the level of the consequences of this threat to the green zone of the matrix, level D4.

H31: Braking system. A power failure of the braking system could cause the collision between two vehicles or with a vehicle and the tunnel, if it reaches a switch too fast. Therefore the consequences of a failure in the power supply of this system can be quite serious, assigning it level 1, while the probability of this occurring is quite low, with a level D. Leaving this threat in the red zone of the matrix, D1. The mitigation measures necessary to reduce the level of this threat are to implement a secondary power supply system that is activated in case of failure of the main one and to have an alternative braking system that works in isolation. If these measures are applied, the level of the consequences of this threat can be reduced to D4, in the green area of the matrix.

H32: Switches. If the switches do not receive power, the vehicle will not be able to make the lane change, which can lead to a collision between two vehicles or between a vehicle and the tunnel. The consequences are serious as it can result in damage to both the vehicle and the people inside, so it has been assigned a level 1. As in the previous cases the probabilities of interrupting the power of this system are small, level D. Due to this this threat remains in the red zone of the matrix, level D1, being necessary to implement mitigation measures. The main mitigation measure is to have a secondary power that comes into operation instantly in case of failure of the main one, thus getting the system back into operation. This would reduce the consequences of this threat to a D4 level.

H33: Tunnel. The systems in the tunnel, such as signaling vehicle location sensors or communications need the power supply to remain constant. In case this fails, collisions of the vehicle with the track can be caused, by reducing the space between them or between two vehicles, so the consequences derived from this are quite serious, having a level 1. The odds instead are small, with a level D. With this, this risk is placed in the red zone of the matrix, D1. The most important mitigation measure in this case would be the implementation of a secondary power supply system capable of keeping the systems active until the vehicle reaches a safe state. Thus reducing the consequences of this threat to level D4, thus moving from the red zone to the green.

H34: Stations. If the stations were left without power, it would be necessary to interrupt the service and their communication with the rest of the systems would be lost. The consequences of this would not be excessively serious as there should be no significant damage either to people or to infrastructure. Therefore, it has been assigned a level of consequences of 5 and a probability of occurrence of D. Thus leaving this threat at level D5, not being necessary mitigation actions.

3.10.5 Energy storage

The risks are associated with energy storage systems, mainly batteries used to power the systems in the vehicle. The use of batteries increases the weight of the vehicle and the chances of a fire occurring inside it, because they tend to overheat. Even so, this is currently the most reliable method, since there is currently no wireless power transmission system applicable to the scale and speed of the Hyperloop. Therefore, when designing the levitation system of the vehicle and others, the weight of the necessary batteries must be taken into account, in addition to the cooling system responsible for keeping the temperature of the batteries within an acceptable range. The batteries will need to be recharged or replaced with new batteries at each stop. The risks considered for this part are as follows.

H35: Increased temperature. If the heat dissipation system fails or is not adequate, there would be an increase in the temperature of the vehicle, which could in the most extreme case burn the batteries. Therefore it has been decided to assign to this threat a level of consequences of 2 and a possibility of occurrence of C. Leaving this threat in the red zone of the matrix, with a risk level of C2, being necessary to apply mitigation measures. The main mitigation measure would be the installation of temperature sensors that constantly monitor it and in case it exceeds a certain threshold send an alert to be able to stop the vehicle before it continues to increase. In addition,

the dissipation systems to be used must be able to function properly under the conditions of the Hyperloop. With this, the level of this threat can be reduced to D4.

H36: Refrigeration liquid renewal error. The cooling liquid is heated to cool the batteries so it will be necessary for it to be renewed in each season by new liquid at low temperature. This exchange must be carried out by means of a hose system that allows the change to be made quickly at the stops. This system may not work properly due to a traffic jam, a failure with the drive pumps or even the station is no reserves of cooling liquid are available. The consequences of this threat are that the vehicle would not be able to leave the station if it has not renewed the liquid, as it would not be able to properly cool the batteries and overheating would occur. So the consequences of this failure are marginal, level 4, since there would be delays, but not great damage and the probability of it happening is remote, because a station runs out of liquid reserves is very unlikely since you must have control of the current level and failures in this type of systems are not very common. This threat would be located in zone D4 of the risk matrix and mitigation measures do not need to be applied.

H37: Cooling liquid leak. It is possible that the circuit of the cooling liquid is not completely well sealed or that a crack occurs in it that causes the liquid to go out. If the liquid that comes out reaches other electronic components not sufficiently protected, it can damage them and prevent them from working properly. These damaged systems could be for example communication or control of the vehicle, which could cause some of the functions to be inoperative, such as the activation of the brake order or communication between the vehicle and the track. Because of this, the consequences of a leak can become critical if they affect an important system, which can cause collisions of the vehicle with another vehicle or against the tunnel. In addition, if the leakage of the liquid do not affect other systems, it would make the cooling of the batteries not enough producing an overheating of the same. The consequences of this threat have been taken as catastrophic, as they can lead to people being injured or even injured, so it has been assigned a value of 1. The probability of such a leak has been taken as remote, as they are quite robust and do not usually fail, unless there is a bad installation or inadequate maintenance. The level of this threat in the matrix is D1 then. The main mitigation measure would be that the circuit of the cooling system is isolated from the rest of the systems, so that in case of the leak it cannot reach them. In addition to this, another measure would be that the electronics of the systems have an adequate degree of protection so as not to suffer damage in case the liquid arrives. If a leak occurs, it is necessary to determine it as soon as possible, so gauges will be installed to measure the pressure of the cooling circuit and to alert in case this decreases too much to stop the vehicle safely as soon as possible. To reduce the possibility of this failure, it is necessary that the cooling system is under an adequate maintenance plan, which allows to detect possible wear or failure that can trigger a leak. With these measures, the level of this threat would move to E4.

H38: Load Failed. The batteries are discharged as the vehicle circulates, so it will be necessary to charge them at each stop at the stations. The charging system can consist of several options, such as a cable connected directly to the vehicle or a system that transmits energy from a contact surface. If the charging system fails, either because the charging station does not have the necessary energy to do so or because of some type of mechanical failure that prevents the

connection from being made properly, the vehicle could not continue circulating. If the vehicle does not have enough battery level to reach the next stop it should not be allowed to leave the station. Because of this, the consequences of this threat are marginal, since the main problem would be that there were delays in the arrivals and departures of vehicles, thus having a level 4. The probabilities of this happening are quite small, since these systems are not very complex, in addition to the fact that the chances of a cut that prevents reloading are small, so a level D has been assigned. Being this threat located in the green area of the risk matrix, level D4.

H39: Changing batteries. It is possible that when changing the discharged batteries for charged ones, a connection failure may occur that does not allow them to feed the equipment properly. This connection error may not be noticeable until the vehicle leaves the station. If the connection failure is not total it is possible that the vehicle does not reach the proper speed to join the flow with the others, being able to produce collisions, but if the failure becomes total the different equipment such as braking, propulsion or levitation would stop working, producing the possible collision of the vehicle with the track or other vehicles. These collisions could be serious as people inside the vehicles could be injured. The consequences of this failure would be quite serious therefore and the level assigned to it is 1, while the occurrence is at level D. With this, the position of this threat in the risk matrix is D1. To mitigate this risk it is important that in the vehicle design you only allow one single fixed position where the battery fits into the vehicle ensuring proper contact between the battery terminals and the vehicle. All batteries found in the backup stations must have passed a check that ensures they are in good condition. In case it happens, it is necessary to equip the vehicle with secondary batteries capable of operating the main systems until reaching a safe area. With this the level of this threat becomes E4.

H40: No availability of charged batteries at the station. It may be that at the time of making the change of batteries there is no charge in the station to replace the one in the vehicle. This would cause delays until a new battery arrives or passengers are switched to another vehicle with sufficient battery. The consequences of this risk do not go beyond delays, so they are not very large, they have been assigned level 5. The probability of this happening is quite small since the stations must have stored enough charged batteries to feed the vehicles that pass through them and once the reserves begin to run out they ask for supply, so the assigned level is E. This threat is then located in the green zone of the risk matrix, E5.

H41: Battery malfunction. Vehicle batteries may stop working properly due to lack of maintenance or connection failures. This would cause vehicle system, such as communications, propulsion, levitation, braking fail, which can trigger quite serious damage to both the vehicle and the people inside. Therefore, it has been assigned a level of consequences of 1 and an occurrence of level C, leaving this threat at level C1, in the red zone of the matrix. It is necessary to implement mitigation measures for this threat such as sensors that constantly monitor the state of the battery and determine in advance a possible failure. This is necessary because the batteries will be constantly in cycles of charge and discharge which will accelerate their wear. In addition, the batteries must be maintained strictly enough to ensure their correct operation and be replaced by new ones once they reach the end of their useful life. This would modify the risk level of this threat to D4, in the green zone of the matrix.

3.10.6 Human failures

It is necessary to take into account the impact that human actions can have on the power supply system, as it can be a major cause of risks.

H42: Lack of maintenance or inadequate maintenance. This could cause systems to malfunction. Therefore, there is a possibility that the system may not be able to provide the power that other equipment needs to function. If this failure occurs with the vehicle stopped the consequences are not very serious, but if it happens with the vehicle driving at high speed it can cause the collision of this with the tracks and the tunnel, injuring the occupants and leaving them exposed to the environment of the tunnel. These exposed consequences are quite critical as they could lead to people being harmed. The probability of this happening can become occasional, level C, if the necessary precautions are not taken. The level of this risk in the matrix is then C1. To mitigate this threat, is to ensure that the maintenance plan to be followed is the right one to keep the system in correct condition. In addition, the personnel in charge of carrying it out must have the necessary training and the correct physical and psychological capacities and a secondary power systems must be available, both for the vehicle and for the infrastructure, so that they are activated allowing the affected vehicles to circulate to the nearest safe area. With these measures, the chances of it occurring are reduced to level D, since being a human error will always exist the possibility and the consequences could be reduced to level 4. Leaving this threat at level D4.

3.11 Communication systems analysis

The communication system is responsible for transmitting the orders and needs of each system, making everyone can operate in a synchronized way and at the necessary time. This system is vital for safety as it is necessary that teams and personnel have all the information they need to be able to function properly. At this point all possible risks detected for this system will be discussed.

3.11.1 Main communication systems

This system is primarily responsible for communications between the different equipment in the vehicle, the infrastructure and the control room, so it is vital that it works properly. The potential major risks have been identified.

3.11.1.1 Data management and processing system

This system will be responsible for processing all the information received and making the relevant decisions depending on the situation. Three possible failure modes have been determined for this system.

H43: Frequency of information. The system is not able to process properly all the information it receives in time because it receives too much information constantly. This could cause the saturation of the system so that it would not be possible to process the information to take appropriate actions. The consequences derived from this failure can become very serious since it can cause delays in communications and in executing orders, such as activating the brakes or switches and some orders could be not even or partially issued. Therefore, the level of

consequences of this risk that has been taken is 2 and the probability of occurring has been taken to level C, since going so fast you may receive a lot of information from many points you pass through. With this, the danger level of this threat is C2, being in the red zone of the matrix and being necessary to apply mitigation measures. The main mitigation measures that must be applied are to place the beacons and other elements of the road that communicate with the vehicle at a sufficient distance from each other so that all the information can be processed correctly. Tests should also be performed to ensure that all the information received by the vehicle during normal operation can be processed in due time. With these measures, the probability of this happening will be greatly reduced to the point that it is almost unlikely to happen, so that the level of the threat passes to the green zone of the matrix, E4.

H44: System reliability. It is possible that the information or orders they transmit are not correct, in this case the system would not be reliable. In the worst-case cause, this could incorrect commands to be issued to the propulsion or braking systems, e.g. giving the order to brake instead to accelerate, causing the collision of two vehicles or a vehicle with the tunnel. Therefore, it has been decided that the level of consequences of this threat is 1, while the probability of this happening is D. Thus, leaving this threat in the red zone of the matrix, with a level D1, having to take mitigation measures. The main mitigation measure will be the test of processes under various circumstances to ensure that it is able to process the information it receives correctly and issue the appropriate orders in each case. Another measure would be to have two processors in parallel that process the same information, check their correspondence and communicate any failure to the control room to stop the vehicle and take the other appropriate measures. This could reduce the likelihood of this happening until it is almost unlikely to happen, and controlling it would have much smaller consequences. So the risk level is reduced to the yellow zone, E3.

H45: System availability. Another important point related to the communication system is its availability, since if the system is not available due to an error that has not been able to be solved it will not be able to circulate normally, though we can use the rest of the systems correctly. Therefore, a level of consequences of 3 and a probability of occurrence of D have been assigned, leaving this threat with a risk level of D3, in the orange zone of the matrix. To mitigate this risk, it is necessary when designing the system to have taken into account the repair times, ensuring that these are the minimum possible. The design should favor that the parts that are most likely to fail can be quickly replaced by new ones. The Mean Time between Failures (MTBF) of the system should also be as large as possible to avoid repair stops. This would increase the availability of the system and reduce the level of risk to D4, moving to the green area of the matrix.

Where possible, and in most conditions, communication between locations, systems and digital hardware platforms should be optical. In the case of safety, it should also be segregated and redundant. Additionally, where possible, it should be physically routed inside the tube, as the tube acts as an effective physical protection barrier and EMF barrier from electrical storms. Optical communications is far less susceptible to electrical storms and EMI from the sun. A trade study must be conducted to evaluate the safety gained versus the design complications of communications hardware in vacuum space.

3.11.1.2 Communication delays

During communication it is possible that delays may occur in the reception or sending of information due to interference or failures in the system, e.g. due to the saturation of the same or the high latency of the system used. There can be delays in communication between two vehicles, between a vehicle and infrastructure elements and between a vehicle and the control room. Where possible, and in most conditions, communication between locations, systems and digital hardware platforms should be optical. In the case of safety, it should also be segregated and redundant. Additionally, where possible, it should be physically routed inside the tube, as the tube acts as an effective physical protection barrier and EMF barrier from electrical storms. Optical communications is far less susceptible to electrical storms and EMI from the sun. A trade study must be conducted to evaluate the safety gained versus the design complications of communications hardware in vacuum space.

H46: pod-pod communication delay. If there is a delay in communication between the vehicles, it is possible that a collision between them will happen, since for example the front vehicle would not be able to inform the vehicle behind in time that it will reduce the speed. *H47: pod-infrastructure communication delay.* A delay in communication between the vehicle and the infrastructure could result in the vehicle being unable to change track or doing so late and colliding with the tunnel. *H48: Delay communication pod-control.* If the delay occurs between the control room and the vehicle, it is possible that the orders sent from the control room to the vehicle cannot be carried out in time, such as the order to perform an emergency braking, which may cause the collision with another vehicle. Due to all this, a level of consequences 1 has been assigned to these three risks and a probability of occurrence D. Being located in the red zone of the matrix, D1, and being necessary to take measures to mitigate them. A mitigation measure would be to employ low-latency communication systems to increase transmission speed. Secondary communication systems dedicated solely to communication between these parts of the Hyperloop can also be used. In addition, obviously the used communication systems must have passed the relevant tests to ensure their correct functioning under the operating conditions. The probabilities of failure would be reduced to almost improbable and the consequences also to have backup systems, moving to the yellow area of the matrix, E3.

3.11.1.3 System Hack

H49: Computer Attack. The communication system can be the victim of a computer attack that compromises communications and cannot be used safely. This can lead to collisions between vehicles or against life if the information they receive is wrong. Therefore, the level of consequences of this threat is 1, while the probability of it occurring is D. Then this threat is located in the red zone of the matrix, D1, needing to employ mitigation measures. The main measure employed is that the communication system must have barriers against computer attacks. These barriers should make it difficult for them to take control of the system and in the event of an attack to alert staff to take appropriate action. A secondary communication system isolated from the main one is another good option in case of attack, to be able to inform and direct the vehicles to a safe area and stop the circulations. Constant monitoring of the state of the communication

system is also useful for detecting possible attacks. The EN TS 50701 standard provides with a helpful approach to achieve a sufficiently low risk and could be reduced to the green zone of the matrix, E4.

3.11.1.4 Location sensors

This aspect of the communications system must be redundant, segregated and the two methodologies used must not have a common mode failure and must be comparative to detect any failure with a sample rate several times more frequent than the fidelity needed to prevent an event identified as the most time critical. This is one of those technology areas that, due to rapid evolution of digital and optical systems, will require a design that allows for rapid evolution.

H50: Sensor malfunction and H51: Out-of-service sensor. These sensors are responsible for determining the position of each vehicle and transmitting it to the control center, in order to avoid possible collisions. For these sensors two possible failures have been defined: 1) that the sensor fails and that the information it sends is not correct; 2) that the sensor is not in operation. In the first case, the information obtained from the sensor would not be reliable and there may be a vehicle in an area, although the sensor indicates that it would not, and in the second there would be no information about the position of the vehicle. Both failures could trigger the collision between two vehicles, so they have been assigned a consequence level of 1, but their probability of occurrence is D. Thus, leaving these risks in the red zone of the matrix, D1. The main mitigation measures that can be carried out to reduce the level of this threat are to carry out a monitoring and maintenance plan of the sensors that allow to verify their correct functioning, detect possible failures and in case it does not work properly, replace it with another. It would also be a good option to have another backup location system, which can be used in case the sensors fail. One of the comparative systems can and should be based completely on firmware, changeable only while the system is offline. Data from this (dumb) system can be constantly compared to the advanced control system using a data diode to prevent any possible corruption of the firmware.

With these measures both the probability of occurrence and the consequences would be reduced, so they would pass to the E2 level of the matrix, in the yellow zone.

This aspect of the communications system must be redundant, segregated and the two methodologies used must not have a common mode failure and must be comparative to detect any failure with a sample rate several times more frequent than the fidelity needed to prevent an event identified as the most time critical. Thus it should be possible to demonstrate by modelling and illustration that hyperloop safety is both redundant and errors well on the side of accident prevention.

3.11.1.5 Monitoring system

H52: Failure to communicate with the monitoring system. This system is responsible for monitoring the status of the different Hyperloop computers and alerting in case of any failure in one of them. The failure may occur in the communication system between the sensors of the monitoring system and the control center. If this happens, it will not be possible to determine in advance if there is a failure in any of the systems or if any of the sensors are failing. The probability of this happening is low, level D, but the consequences could become quite serious if the correct functioning of the systems cannot be verified so the level of consequences chosen is 2. Thus remaining in the orange zone of the matrix with a level D2. The best way to mitigate the effects of this threat is to install a

secondary communication system between the control center and the monitoring systems so that in case the main one fails, this can be used until the other one is repaired. This reduces the level of this threat to D4, becoming in the green zone of the matrix.

3.11.2 Human failures

It is necessary to take into account the impact that human actions can have on the communication system, since it can be a major cause of risks.

Human failure is an excellent example of the type of data that can be transferred from air travel events and failures for application to hyperloop, as indicated above.

H53: Lack of maintenance or inadequate maintenance. It is possible that the maintenance of the communication system has not been carried out or has not been done correctly. This could cause systems to malfunction. Therefore, there is the possibility that the system is not able to function properly and transmit to the vehicle the orders or information it needs to be able to circulate. In this case the vehicle could not be controlled properly and could lead to collisions with other vehicles, not being able to communicate to the vehicle that there is another nearby, or with the tunnel, because it cannot warn the vehicle that a switch is nearby to brake for example. These consequences are quite critical as they could lead to people being harmed. The probability of this happening can become occasional, level C, if the necessary precautions are not taken. The level of this risk in the matrix is then C1. To mitigate this threat the main thing would be to ensure that the maintenance plan to be followed is the right one to keep the system in correct condition, in addition the personnel in charge must have the necessary training and the correct physical and psychological capacities. In addition, secondary communication systems must be available between the main equipment to allow the vehicle to continue circulating safely to a safe area. With these measures the chances of occurrence are reduced to level D, since being a human error will always exist the possibility, and the consequences could be reduced to level 4. Leaving this threat at level D4.

3.12 Interfaces system analysis

This point refers to the main interfaces between the different systems to keep them connected to each other and that they can function correctly and synchronized. The main risks identified are as follows.

H54: Power System Interface. This is surely the most important interface, since all other systems depend on the necessary electricity supply to be able to operate. Therefore, if there is a failure in this interface with any of the systems, it would stop working, which could affect propulsion, levitation, communications, control. Because of this the level of consequences that has been assigned to this threatened is critical, since if the systems stop working it cannot circulate and there could be a collision between two vehicles that damages both people and vehicles. The occurrence that has been determined is occasional, level C. With this this threat is located in the red zone of the risk matrix, level C2. The main mitigation measure is that if a system loses power, an alert must be issued to inform the personnel on board the vehicle and the control center, and

the appropriate emergency systems must be activated depending on the system that has failed (auxiliary power supply, emergency brake, wheel deployment). It is also important that the maintenance plans are carried out are strict enough to prevent this situation from occurring or to reduce the occurrence. With this, the level of risk becomes D4, remaining in the green area of the matrix.

H55: Braking curve. The braking system must be able to determine the optimal braking curve that allows the vehicle to be stopped at a safe distance. The interfaces with the infrastructure must work properly, to ensure the braking before a danger point or a forced stopping zone or even enter a curve with higher speed than it should. The level of occurrence of this risk has been taken as occasional, level C, and the severity of the consequences as catastrophic, level 1. This risk being at level C1 of the risk matrix. To mitigate this threat, it is necessary that the information from the signalling system received by the vehicle to determine an appropriate braking curve. A redundant communication system between the track and the vehicle is a good option to ensure the necessary information. It is necessary that the braking system has passed the operating tests to verify its ability to function properly. The level of risk when applying these measures would be reduced to E2, passing to the yellow area of the matrix.

H56: Dynamic braking control. This risk is related to the previous one, but it deals with how the system should modify the braking curve depending on the speed and position of the tail of the front vehicle to maintain a safety distance that allows at braking in case of breakdown. The main risk is that the communication between the two vehicles fails and a correct braking curve cannot be generated, which would cause the collision of the two vehicles. The level of consequences of this risk has been taken as catastrophic, level 1, and the probability of occurrence as occasional, level C. So with this this risk is placed in the red zone of the risk matrix, level C1. The main measure to mitigate this threat is a secondary communication system between the vehicles to ensure that the information is transmitted correctly. It would also be necessary to carry out tests under the actual operating conditions to verify that the system is capable of modifying the braking curve based on the information it receives from the front vehicle. If these measures are taken, the level of risk would be reduced to E2, thus placing it in the yellow part of the matrix.

H57: On-track signalling system with vehicle. It is vitally important for the operation of the Hyperloop that the interfaces between the track signalling system and the vehicle operate properly. Due to the high-speed that Hyperloop reaches, it is very difficult for a person to handle the vehicle, since it would not give him/her time to see the signals and act accordingly. That is why the vehicle must receive the information from the signalling equipment, process it and execute the appropriate action, accelerating or braking. If the interface between these systems fails, the vehicle would not be able to modify its speed automatically according to the circumstances of the track. This could lead to collisions between vehicles or between a vehicle and the tube. The vehicle could not receive the notice that it must stop if there is a vehicle standing in front or that there is a change of track that in false position. As you can see, the consequences of an error in this interface could become fatal, since the vehicle could circulate without knowing the circumstances of the road, which could lead to accidents with injured people. The consequences of this risk is a crash in which the vehicle, the tunnel or the people are damaged and there may even be serious

injuries or deaths, so it is assigned level 1. The chances of this happening can become occasional, since when circulating at such a speed there are not yet defined enough systems to transmit without any failure the information, because of this it is assigned a level B of occurrence. This risk is therefore in the red zone, level B1, of the risk matrix.

The main mitigation measure for this risk is that there is a secondary communication system, in parallel with the main one as a backup, so that in case one fails the other can be used. This system must be constantly monitored to ensure its correct operation and, in case of showing any indication of failure, send an alert to stop the vehicle safely and be able to correct the error before it going further. It is necessary that this interface is sufficiently tested to ensure a correct operation, with some tests that confirm that the system works in the conditions limit of use. With these measures this risk could be reduced to the D4 level.

It could also be mitigated by designing a redundant comparative system with no common mode of failure.

H58: Interface between control room and pod fails. When the vehicle circulates, at such high speeds it is likely that it will not be driven by a driver inside the driver, but will operate automatically, under the supervision of the control room staff and control subsystems. The personnel must be responsible for checking the functionality of said redundant subsystems assuring that the speeds of the vehicles are within the limits established for each area of the track and that the distances between vehicles and routes are adequate to avoid collisions. In case the automatic control system of the vehicle fails, the staff must realize and apply the appropriate measures to avoid damage. If this interface between the vehicle and the control room fails, the control room would have no information about the vehicle's status or the ability to stop it. This could cause the vehicle to circulate out of control and could lead to collisions with the tube or another vehicle, causing people inside to be seriously injured. Because of this the level of this threat is 1 and the probability of it happening is C, since due to high speeds or areas that are further away it may be that communications fail. The level of this risk in the matrix is located in the red zone, level C1, being necessary to apply mitigation measures. The main measure to reduce the level of this threat in the array would be to implement another interface, a secondary communication system between the vehicle and the control room, which could be used in case the main one failed. In addition to this, the system must be constantly monitored to verify that the communication is still operational and in case it is not so send an alert to be able to notify the personnel and take the appropriate measures. If the vehicle loses communication with the control room, it would be important that it is able to automatically move to reach a safe area to stop until the problem is fixed. With all this the threat level is reduced to D4.

3.13 Control-command analysis

The control-command system is responsible for controlling the actions of the other systems, giving them the right orders at the right time. This system must work properly so that everyone else can do it too. Therefore, it is important to analyze the main risks of this system to try to mitigate its effects as much as possible. Within this system, the following possible failure modes have been determined.

H59: System Hack. The control-command system is also susceptible of computer attacks. An external person could take possession of the system, control the vehicle and causing possible damage to the people and the vehicle. Therefore, the consequences of this threat are level 1, and the chances of them occurring are low, level D. Then this threat is located in the red zone of the matrix, with a level D1. The main mitigation measure is the use of cybersecurity systems that provide protection and alert personnel in the event of an attack, so that they can send the order to recover to a safe area and stop there. Another option would be the implementation of a secondary independent, physically segregated not hackable (such as isolated firmware with the only interface being a local manual connection) type of control system to activate in case of emergency. All critical events involving capsule travel should be protected against using a secondary system that is physically segregated and cannot be hacked, such as isolated firmware with the only interface being a local manual connection. Version control and test bed verification is also essential to ensure that latent errors and compromised updates are not installed. These measures would reduce the level of risk to the green zone of the matrix, E4.

H60: Software failure. The system could not able to process the information properly, so that the orders it sends to the systems are incorrect. This failure would be very serious since it could turn out that it ordered to accelerate the vehicle instead of braking, being able to cause damage both to the vehicle and to the people inside. Because of this the level of consequence that has been taken into account is 1, while the probability of occurrence is low, level D. Thus remaining in the red zone of the risk matrix, level D1. The most important possible mitigation measures would be the use of a redundant control system and that the response of both should coincide, differently reporting an error in one of the systems. Another important aspect is that the control-command system must be sufficiently tested to ensure its correct operation under normal operating conditions. With this the level of this threat could be reduced to E3, moving to the yellow zone of the risk matrix.

H61: Hardware failure. It is possible that the control-command system fails due to a hardware error, which can cause some faulty component, due to lack of maintenance or sabotage. This can cause the control system to become inoperative and damage vehicle and people, due to a possible collision with another vehicle or against the tunnel. Therefore, the level of consequences assigned to it is 1 and the probability is average, level C. This threat is therefore in the red zone of the matrix, C1. The possible mitigation measures applicable for this case are the physically robustness to withstand normal operation, protected to avoid manipulations from the outside by people, who do not have the permits to do so, carry out an adequate maintenance plan of the system to verify its correct operation and quickly replace the failed parts to reach the end of its lifecycle and finally it can be used redundant systems to use in case of fails. If these measures are applied the level of risk can be reduced to E4, moving to the green area of the matrix.

H62: Erroneous activation of a route. There may be a situation where a control room operator accidentally or mistakenly triggers a track change that should not be activated, either a high-speed or a conventional one. If a vehicle passes through that switch at the time of the erroneous activation, there could be a situation where the vehicle crashes into the tunnel if it cannot change the track in due time or it collides with another vehicle heading in the opposite direction or

standing on the invaded track. Another possibility is that the vehicle made the change of track without colliding with anything, but its path would be modified. The level of probability of occurrence of this failure has been estimated in remote, level D, but the consequences that can entail could be catastrophic in the event of a collision, so it has been assigned a level 1. This threat is therefore located in the red zone of the matrix, level D1. The main mitigation measure is that those responsible for carrying out the tasks of control and command must have the necessary training, in addition to adequate physical and psychological capacities. To avoid collisions, the guidance system should not allow the activation of the track changes if there is a vehicle close enough to that switch, thus avoiding that in case of accidental activation the vehicle crashes into the tunnel because it has not enough time to change. Collision between two vehicles can be avoided if the distance between the vehicle standing or driving on its road properly and the switch is large enough for the two vehicles to brake before colliding. This distance is a function of the speed at which the vehicles circulate in each area and must be highly controlled and it may be necessary to decelerate or even stop the vehicle to maintain it.

Finally if there is no collision the vehicle will have deviated from its track, so it will be necessary to alert the other vehicles of this change and look for an alternative route or an area to be able to change direction safely and return to the original path.

Other mitigation measure is to verify feedback from the capsule monitoring safety system that would automate and prevent any such erroneous human input, instead giving immediate feedback that the requested action can not be executed for the approaching capsule.

With these measures the level of this threat can be reduced to E3, moving to the yellow zone of the matrix.

H63: Erroneous activation of the braking system. It is possible that its causes an accidental activation of the vehicle braking system by an error of a control room operator, software or the driver, in case the vehicle has it. If this happens, the vehicle would decelerate and could collide with a following vehicle running at normal speed. The probability of this failure occurring is remote, level D, and the consequences can become moderate, level 3, if the collision occurs. Being the level in the risk matrix the D3. The best mitigating measure is to ensure that the persons in charge of the control of the vehicle have the appropriate training and are in the correct mental and physical conditions to carry out their work. Another way to avoid this is through the communication system between vehicles, which allows the vehicles to have information on the speed and position of other vehicles and can adjust their braking curve accordingly. Therefore, it must be ensured that this system works correctly by monitoring its condition and proper maintenance. With these measures, the level of risk of this threat could be reduced by moving to the green zone, level E5.

H64: Erroneous activation of the propulsion system. The propulsion system can also be activated incorrectly, due to a failure of the control center operators or the onboard driver, if any. This failure could cause the vehicle to accelerate too much when it reaches a switch, which could cause a collision with the tunnel in the worst case, to enter a station with high speed or for the vehicle to collide with another in front driving at normal speed. The consequences of this error are critical, level 2, and the occurrence is D-level, remote. Thus obtaining a level D2 in the risk matrix. As with

all other risks due to human error, the primary mitigation measure must be to ensure that the personnel in charge of these operations have the necessary capabilities and are in the right condition. To avoid collisions between vehicles it is important that the communication system between them works correctly to adapt the braking curves depending on how the adjacent vehicles circulate. To avoid entering dangerous points, such as switches or stations, too fast, it would be advisable for the system to set a maximum vehicle speed depending on which area it is in. For example, if the vehicle approaches a switch, the beacons warn it and it limits the maximum speed at which it can circulate automatically, avoiding possible accelerations. If these measures were taken into account, the level of risk in the matrix would be reduced to E4, in the green zone.

H65: Lack or inadequate maintenance. It is possible that the maintenance of the control-command system has not been carried out or that it was not correct. This could cause systems to malfunction because they cannot be properly controlled. The vehicle would not be able to execute the necessary commands, such as braking when arriving at the station, at a switch or when approaching another vehicle, and collisions with other vehicles or with the tunnel could occur. These exposed consequences are quite critical as they could lead to people being harmed. The probability of this happening can become occasional, level C, if the necessary precautions are not taken. The level of this risk in the matrix is then C1. To mitigate this threat the main thing would be to ensure that the maintenance plan to be followed is the right one to keep the system in correct condition, in addition the personnel in charge of carrying it out must have the necessary training and the correct physical and psychological capacities. In addition, secondary control systems must be in place for the main equipment that allow the vehicle to continue to circulate safely to an area where there is no danger. With these measures the chances of its occurrence are reduced to level D, since being a human error will always exist the possibility and the consequences could be reduced to level 4. Leaving this threat at level D4.

H66: Absence of action protocols. Being a novel system, it is possible that the correct protocols of action are not available for certain situations that have not been taken into account. This could lead to a collision between vehicles or against the tunnel if the vehicle or staff are not able to make the right decision in a novel hazard situation. The consequences of this would become quite serious, level 2, since depending on the situation there could be injuries. The probability of its occurrence is E, since most of the possible scenarios must be taken into account in determining the protocols and it is very unlikely that it has not been taken into account before. The threat level of this risk in the matrix is then E2, in the yellow zone, not needing mitigation measures.

A thorough analysis and resulting bounding conditions must be developed, using either STPA/STAMP or a similarly sophisticated platform.

3.13.1 Electro-Magnetic Compatibility (EMC) analysis

This will address the risks related to the electromagnetic compatibility of different systems and the dangers that can arise for people. Two main risks are detected.

H67: Electromagnetic interference. The different systems of the Hyperloop running at the same time can cause interference with each other, especially the main cause of interference can be the

levitation system, since the magnetic field generated is quite large. This electromagnetic interference could also affect passengers with medical devices implanted, such as pacemakers. Because of this, it is very important that this interference does not occur, so that all systems work properly and passengers can travel safely. The consequences of this type of threat have been classified as 1 and a medium-high probability of occurring due to the characteristics of the Hyperloop, level B. Being the level of this threat in the risk matrix B1. Currently not much information is available on electromagnetic interference generated by a Hyperloop specifically, so the first mitigation measure would be to test under normal operating conditions to see how the system behaves in this regard. As a result, this is listed as future research. Depending on the result of the tests, the appropriate measures should be taken to avoid this type of failure, such as shielding certain parts of the tunnel and the vehicle. In the case of passengers it would be important that the area in which they are located is if it is screened to avoid these possible interferences. Current standards, such as EN 50121 for emission or limits used in similar systems, such as magnetic levitation trains, can be taken as references for design until specific tests will be done and Hyperloop-specific data are available. With these measures, the level of risk could be reduced to E3, thus reaching the yellow zone.

Procedures used in aviation for Electro-Magnetic Compatibility (EMC) testing can also provide insights to be used in Hyperloop. In particular the RTCA/DO-160 standard is of relevance. This standard defines several tests that could be applicable for Hyperloop such as those in sections: 15) Magnetic Effect; 16) Power Input; 17) Voltage Spike; 18) Audio Frequency Conducted Susceptibility - Power Inputs; 19) Induced Signal Susceptibility; 20) Radio Frequency Susceptibility (Radiated and Conducted); 22) Lightning Induced Transient Susceptibility; 23) Lightning Direct Effects; 25) Electro-Static Discharge (ESD). In addition to EMC, in aviation also the High Intensity Radiated Fields (HIRF) and lightning are important. For lightning RTCA/DO-160 (chapter 22) and the latest version of MIL-STD-461 (Revision G) are relevant, while for HIRF it is the FAA HIRF Rule & Advisory Circular 20-158. Some precautions against interference can be part of the software development. Standard techniques and measures of data validation and error correction could be used. From [Williams, 2017]: *Some means of disabling software error-checking is useful when optimizing the equipment hardware against interference, as otherwise weak points in the hardware will be masked by the software's recovery capabilities. For example, software which does not recognize digital inputs until three polls have given the same result will be impervious to transients which are shorter than this. If your test uses only short bursts or single transients the equipment will appear to be immune, but longer bursts will cause mal-operation which might have been prevented by improving the hardware immunity.*

H68: Induced stress. Another major risk is that tensions may be induced in certain parts of the vehicle that may affect systems or people inside. Because of this, the level of consequences of this threat has been taken as 1 and the probability of occurrence as medium level, level C. With this, this risk would be placed in the red zone of the risk matrix, at level C1. As in the previous case there is not enough information currently on the induced stresses in the specific case of Hyperloop, so the first thing would be to perform tests to see how it affects and take the appropriate measures to avoid possible risks. They can also be taken into account until particular data are available for

the Hyperloop current standards such as EN 50121 or the limits of magnetic levitation trains, as they are the most similar at present. This could reduce the level of the threat in the risk matrix to the E2 level, placing it in the yellow zone.

3.14 Pod system analysis

The pod is the Hyperloop subsystem that includes the cabin where people and goods are transported. . It travels inside the tunnel and, when it is designed to transport people, it must be pressurized so that passengers can breathe. We have identified several risks related to the vehicle's components.

3.14.1 Air/oxygen supply

This system is responsible for maintaining optimal pressure and oxygen levels for passengers in the vehicle. This should be at least 95% covered by air travel knowledge and space travel.

H69: Pressure supply failure. When the pressure supply fails, it falls causing passengers to suffer damage or die. The severity level is 1 (catastrophic) so it should be avoided at all costs. The probability of occurrence is remote (level D). As a mitigation measure, the distribution of oxygen masks is proposed in case of failure in the supply; this would minimize the severity.

H70, H71 and H72: Oxygen supply failure. Furthermore, if there are failures in the oxygen tank, the oxygen supply will fail due to its cracks or explosion. Although the probability of occurrence is remote, the consequences would be equally catastrophic since they endanger human health and can trigger the death of people. As mitigation measures, it is proposed to use a redundant oxygen tank, the placement of emergency doors, exclusive fire extinguisher and detection system for this component and a measurement system, by which anomalies in the system can be identified in time. Also, the tank should be maintained properly. All these measures will decrease severity to moderate. This would reduce the level of threat in the risk matrix to the D4 level.

3.14.2 External structure

The outer structure of the vehicle is what confers enough stiffness and structural resistance to the vehicle.

H73, H74: Excessive load > deformation > pressure leak. An excess of load in the cabin could cause deformations that could lead to cracks and expose passengers to the vacuum environment, being the consequences catastrophic (level 1) although with a remote occurrence. As a mitigation measure it is proposed that the structure should be designed with a greater than usual safety factor. These measures would reduce the severity of the risk to moderate.

H75: Vibrations. In parallel, an excessive level of vibration could cause discomfort to the passengers, however, this is a level 5 likely risk.

3.14.3 Vacuum vessel

The vacuum container is the place within the vehicle where the vacuum is settled, namely, the inside of the vehicle, where people and goods travel.

H76: Cracks and leaks. In this component, leaks or air leaks can occur due to cracks derived from poorly tightened screws, poorly closed doors, dilated joints, etc. These leaks would cause the depressurization of the cabin. Due to how often the materials wear out, the risk has been classified with a likelihood of occasional and moderate severity. By incorporating a leak detection system and performing maintenance works frequently, the severity of the risk would decrease to moderate.

3.14.4 Heat Ventilation and Air Conditioning (HVAC) equipment

The air conditioning and ventilation system wish to provide passengers with comfort.

H77: Heating Failure: if the HVAC system fail, passengers would be cold and, depending on how long the cooling system would be out of working, could even cause harm to people, so it is considered a risk with a level 4 severity and a probability of occasional occurrence. If the HVAC system has a redundant installation, the severity of the risk would decrease to tolerable.

H78: Air conditioning failure. Similarly, if the air conditioning system fails, passengers could suffer heat stroke or simply not be comfortable, which would mean a level 3 with unlikely severity and level 5 severity but probable respectively. A redundant cooling system is proposed as a mitigation measure.

3.14.5 Lighting

H79: Malfunctioning of the lighting system. A malfunction of the luminaire system would cause passengers to be uncomfortable, assuming a low severity of level 5. It is a risk that can occur occasionally.

3.14.6 Fire Protection Systems (FPS)

H80: Fire extinguishers failure. The installation of fire protection is essential to deal with possible fires that may occur, therefore, a failure in this system would be catastrophic, because it could not protect facilities and persons. The probability of occurrence is remote. Periodic reviews of the status of the FPS can reduce the severity of the risk to moderate.

3.14.7 Emergency equipment

H81: Emergency system failure. Similarly to FPS, if the emergency systems fail, in such a way that the emergency alarms do not work, it would mean not being able to mitigate the emergency in time, putting both the system and the passengers at risk. The consequences could be catastrophic. The probability of occurrence is remote. If periodic reviews of these systems are performed, the severity of risk decreases to moderate.

3.14.8 Doors

The doors of the vehicle allow the entry and exit of passengers.

H82: Door seal failure. Failure to seal the doors would cause depressurization of the cabin, which could cause harm to passengers (level 3). On aircrafts, the doors are kept tightly closed because of the difference in pressure between the outside and inside. This would happen likewise in a Hyperloop system; the difference of pressure between the tunnel and the vehicle's interior would help to keep the doors closed.

H83: door open/close system failure. In addition to the common doors, there are the evacuation doors, which, in the event that they fail, would prevent the evacuation of passengers and the consequences would be catastrophic. The probability of the occurrence of the aforementioned risks is remote. The placement of sensors to monitor the current state of door seals and a periodic review of them can cause the severity to decrease to marginal and moderate, respectively.

3.14.9 Belt seats

H84: Malfunctioning. A failure in the seat belts of the passengers is a remote risk but could cause damage to them so it is considered a risk of severity 3. As a mitigation measure, it is proposed that a periodic review of the condition of seat belts be carried out, reducing the severity to marginal.

3.14.10 Propulsion/braking from the interior

H85: Pod unable to brake, H86: Pod unable to accelerate. The vehicle's propulsion and braking system may fail due to system anomalies, either because the vehicle cannot brake or because it cannot accelerate. They are remote risks, however, the severity of the nonbraking would be catastrophic because it could cause the collision between one vehicle and another vehicle at very high speeds. The severity of the inability to accelerate would be critical because it would cause delays in service.

3.14.11 Electronics

The vehicle consists of a system of electronic circuits that make the electronic components work.

H87, H88: Short circuiting of electronics. A short circuit could cause small fires and/or system disruption due to some components going down. These risks have a level 3 severity and a probability of remote occurrence.

3.14.12 Batteries

Batteries are the components that supply energy to the vehicle.

H89: Excessive heating, H90: Explosion. Excessive heat or an explosion outside can cause the batteries to explode. The consequences would be catastrophic as there would be fires, structural and plant damage and damage to passengers. The probability of occurrence is remote. A mitigation measure can include fire sensors. Then, the occurrence will be improbable.

To maintain this event as improbable, evidence-based inspection, testing and battery health monitoring is essential. Large battery systems are rapidly being deployed in passenger and commercial transportation systems, which will lend essential data and lessons to hyperloop safety.

3.14.13 Low-speed wheels

Low-speed wheels are used by the vehicle to move when it is entering or leaving the station. In addition, in the event that the vehicle runs out of energy, these wheels would serve to move the vehicle inside the tube.

H91: Deployment failure. H92: Retraction failure. A failure in the output of the wheels would cause the vehicle to become stuck in the tube. Meanwhile, a failure in the retraction of the wheels would cause the vehicle to collide with the track. Both risks assume moderate severity. The probability of occurrence is remote.

3.14.14 Sensors and location

The sensors and the vehicle's location system are intimately linked to the entire signalling.

H93: Incorrect data collection. The sensors allow at knowing what the current state of the vehicle is and the location allows at knowing its position. A failure in this type of signals would cause the vehicle to be out of control and could cause several vehicles to collide with each other, posing a critical risk. The probability of occurrence is remote and severity is 1 (D1).

A mitigation measure could be that both safety and non-safety location data acquisition would be based on multiple independent systems. One should be on board the capsule, and not depend on remote signals, but should be determined by track location-specific indication, such as localized passive indicators read by onboard systems. This data can then be time stamped and compared to centralized operating system data for integrity and safety.

3.14.15 Connection to the control system

H94: Lose connection. A loss of connection with sensors and location systems could cause the collision of two vehicles, posing a critical risk. The probability of occurrence is remote.

3.14.16 Noise

H95, H96, H97: Noise pollution. It derives from the Hyperloop system and, in particular, from the movement of the vehicles that can cause alterations in the environment and inside the system causing disturbances in the environment (probable occurrence), discomfort in nearby residential places (occasional occurrence) and discomfort of passengers (remote occurrence). These risks have been classified as marginal.

3.14.17 Entertainment and information on board

As in other transport systems, the Hyperloop will have onboard multimedia entertainment system for passengers.

H98: System failure. It would cause inconvenience to passengers, but the level of risk is negligible and the probability of occurrence is remote.

3.15 Infrastructure Analysis

Infrastructure subsystem referees to tunnel, tube, pylons, track and the needed equipment to keep the vacuum.

3.15.1 Tunnel

The tunnel encompasses the tube and its supports, tracks, rails, vacuum pumps, wiring, structural junctions and track changes. A vacuum environment is guaranteed in the tube, which is the key for the vehicle to reach high speeds. Long tunnels may include safe areas (Lyngby, Grøvn, Myklebust, 2020).

3.15.2 Tube

The tube is the structure through which the vehicle slides. It provides sufficient rigidity to the system, contains vacuum, supports the tracks and serves as a means of transporting energy. Several types of risk are contemplated in the tube.

H99: Structural damage resulting from corrosion, shocks or perforations. This can cause tube cracks that pose a moderate risk. The probability of occurrence is occasional.

H100, H101: Structure expiration due to exceeding Serviceability Limit State (SLS) or Ultimate Limit State (ULS). This would cause discomfort in passengers and friction between the vehicle and the track. The first risk is moderate, however, the second could become catastrophic. The probability of occurrence is remote.

H102: Welded or bolted joints failure due to loosened screws or solder wear. They could cause problems with cabin pressurization, posing a moderate severity risk. The probability of occurrence is remote.

H103: Presence of objects that block the tube. This would cause damage to the vehicle and the consequences could be catastrophic. The probability of occurrence is remote.

H104: People trespassing the tube. This risk depends on the design of the stations and accessibility of the tube. In the worst case, if a person accesses the tube, although unlikely, it could cause death or very serious harm to that person. Therefore, this risk is classified with severity level 1.

3.15.3 Pylons

Pylons are the structures that support the tube and absorb its vibrations.

H105: Pylon structural deformation. A deformation in the pylons could cause the tube to deform, causing the vehicle and track to touch each other, causing catastrophic accidents. The probability of occurrence is remote.

3.15.4 Track

The tracks are responsible for guiding the vehicle.

H106: Track deterioration. If the tracks deteriorate, they could cause the vehicle and track to touch, with catastrophic consequences. The probability of occurrence is remote.

3.15.5 Vacuum pumps and valves

Vacuum pumps and valves create and maintain vacuum in the tube. Several risks can be considered in this subsystem:

H107: Pump or valve failure in the tube. It is not to be possible to maintain the vacuum in the tube, which would mean lower speeds of the vehicle, even if the system does not work. The severity of this risk is moderate. The probability of occurrence is occasional.

H108: Failure of the airlock pump. It would cause airflow in the vehicle that would involve greater effort when dragging the vehicle. It is a risk of moderate severity. The probability of occurrence is occasional.

H109, H110: Overheating of the pump. It could cause explosions in the tube or air lock. Both risks would have consequences of critical severity. The probability of occurrence is remote.

H111: Interrupted power supply. The pumps would stop working or valves are malfunctioning, there would be no vacuum and the vehicle would not be able to move. The consequences of this situation would be of a critical level. A redundant electrical system would significantly reduce the level of risk. The probability of occurrence is occasional.

3.15.6 Rails

The rails serve as a guide for low-speed wheels.

H112: Deformation, deterioration, etc. If the rails suffer deformations due to wear and deterioration, there would be problems fitting the wheels to the rails, which would prevent the vehicle from entering or leaving the station. This is a moderate-severity risk. The probability of occurrence is remote.

3.15.7 Joints in the tube

H113: Tube joints failure. The joints of the different sections of the tube can be damaged causing the tube deformation and, consequently, vehicle and tube to touch each other. It is a risk of critical severity. The probability of occurrence is remote.

3.15.8 Wires

The wiring system is responsible for transporting electricity to the entire system. Wiring in general, and significantly the power cabling and signaling runs should not be in the vacuum envelop. They will off gas, become brittle and be very difficult to inspect and modify.

H114, H115: Cable damage. H116: Cabling defect. If the wires are damaged it could lead to power outages, the inability to brake the vehicle using the motors, and/or the cables become unprotected. Although the probability of occurrence of these risks is occasional and unlikely, respectively, the severity of the damage would be critical in the first two hazards and catastrophic in the last one.

3.15.9 Switch

Pathway changes allow the vehicles to be directed where appropriate.

H117: Switch failure. If the change of track fails, the vehicle would make a route that does not correspond to it and could cause the collision with another vehicle, being a critical risk. The probability of occurrence is remote.

H118: Magnetic force debilitation. To carry out the movement of the tracks, a magnetic force is necessary. If it weakens, it will not be enough to make the change of routes and can cause the collision of the vehicle with the track. The probability is remote and the severity considered is critical.

H119: Communication failure. If the communication system fails, the track changes could be ordered late and could cause the vehicle to collide. It is a risk of critical level of severity and with occasional occurrence.

H120: Power Outage. If the power supply fails, the change of track is not carried out and could cause the collision of the vehicle. It is a risk of critical level of severity and with remote occurrence.

H121: Vibrations. In addition, the change of pathways can cause vibrations that are annoying for the environment, being in this case the risk of level 2 and the occurrence occasional.

Wiring in general, and significantly the power cabling and signaling runs should not be in the vacuum envelop. They will off gas, become brittle and be very difficult to inspect and modify.

3.16 Terminal and station analysis

The terminal and station, as in other means of transport, is where passengers begin or end their journey. This establishment is where the vehicles arrive and from where they leave, so it will be composed, at least, of a platform on which the passengers move. The movement of the passengers must not influence the vacuum generated in the system. Some risks have been identified due to failures in the following subsystems.

3.16.1 Airlocks

Airlocks are responsible for regulating pressure from atmospheric pressure at the terminals to vacuum pressure in the tube, and vice versa. Aerospace data should be extensively analyzed and extrapolated to the hyperloop.

H122: Airlock gate failure. If the gates of the lock failed, the vehicle would not be able to enter or leave the station, being a moderate risk with a probability of occasional occurrence.

3.16.2 Boarding/aligning equipment

The access platform that connects the terminal with the vehicle allows passengers to access it.

H123: Boarding/alighting equipment failure. There is a risk that this platform will not function properly, which would prevent passengers from boarding or disembarking. Being a risk of marginal severity. The probability of occurrence is occasional.

Docking systems such as the space station have generated extensive knowledge useful to hyperloop. The knowledge being made transparent and available to the public will greatly boost confidence in the public.

3.16.3 Pod load/unload system

This system allows the loading and unloading of goods in/from the vehicle.

H124: Pod load/unload equipment failure. If the equipment of this system failed, the vehicle could not leave the station either because it was not possible to unload the goods from the previous trip or because it was not possible to load the merchandise for the current trip. The probability of occurrence is remote and the severity is critical because it would cause interruption of service and delay in goods deliveries.

3.16.4 Building

H125: Collapse. The terminal building can pose a very unlikely risk of collapse that would have catastrophic consequences.

3.16.5 Docking services

The Hyperloop applications for the transport of goods introduces a specific risk.

H126: Failure in coupling at docking point. The services of loading and unloading of goods in the stations pose a risk of dock or platform loading and unloading fails, which would prevent to complete operation and would imply delays. Therefore, it is a risk of marginal severity and the probability of occurrence is occasional.

3.16.6 Passenger flow control

This component of the terminal is related to the design of passenger routes inside the terminal.

H127: Failure in passenger flow management. A bad design of these routes could cause people to gather or have difficulty getting around the terminal. This is a risk that can occasionally occur, but its severity is tolerable.

3.16.7 Integration with existing infrastructures

The integration of the Hyperloop system consists of the integration of the Hyperloop stations with airports, train stations, etc.

H128: Integration with other infrastructure systems like airports, stations, etc. It may pose a risk to the extent that such integration will lead to interference between modes of transport. It is a risk

that should be taken into account a priori in the design phase of the terminals, so it has a probability of remote occurrence once the system is already implemented and has a marginal severity.

3.16.8 Elevators, escalators, stairs

H129: Passengers injuries. In this type of element, the risk is that there are passengers who fall, which would be a moderate risk, but that could be mitigated by taking measures such as informing passengers of how to use the stairs or using fluorescent lights and other appropriate signalization. The probability of occurrence is occasional.

3.16.9 Emergency exits

H130: Inaccessible emergency exits. If emergency exits are not accessible in an emergency, it would be a critical risk because it would prevent the evacuation of people in the terminal. The probability of occurrence is remote.

3.16.10 Fire Protection System (FPS)

H131: Fire. In the event of a fire, if the FPS failed, it would be a risk of critical severity as people could not be protected. The probability of occurrence is remote.

3.16.11 Platform

The platform is the place where passengers get on or off the vehicles.

H132: Excess passengers on the platform. An excess of passengers on the platform can produce crowds that obstruct the platform and can even cause falls. This poses a moderate risk so the platforms and schedules must be designed in such a way as to avoid crowds on the platforms. The occurrence is probable.

3.17 Signalling system analysis

The signalling system is part of the control and communications system. In particular, it encompasses all signals related to vehicle and pathway positions. The following risk have been detected.

3.17.1 Vehicle detection systems

Problem could arise for dynamics and positioning, as well as for stopping point protection.

H133: Vehicle position detection error. This system allows at detecting the position of the vehicle. If this system fails, it could cause the control system to give erroneous orders and the possible collision between two vehicles, the severity of the risk being catastrophic. The probability of occurrence is anyway remote.

H134: Error in the pod expected stopping point. This system detects where the vehicle should stop. If this system fails, the vehicle could stop where it should not and could collide with another vehicle

or even with the track, being the consequences catastrophic. The probability of occurrence is remote.

3.17.2 Routing (detours)

This part of the signalling system is responsible for sending the signals to change the position of the tracks and thus direct the vehicles. In this system, you can find several risks.

H135: Blockage of the movement of the tracks. If it is not possible to change the position of the tracks, the vehicle could collide with them, with catastrophic consequences.

H136: End of stroke detection. If the system that detects if the tracks are in correct position stops working, it would force the service to stop and cause delays. In the worst case it could cause the vehicle to collide with the route or another vehicle, the consequences being catastrophic.

H137: Failure in the locking system. If the tracks were not well fixed, it would make the vehicle have to slow down or even stop. It would be a critical risk. The probability of occurrence of this risk is remote.

3.18 Interlocking system analysis

This is the system of movement authorization by control signals. Within this system, there are several risks.

H138: Failure in the protection of the tracks.

H139: Failure in the control and coordination of signals.

H140: Failure of the signals pass-through authorization system.

Moreover, the Following specific risks have been detected.

3.18.1 Sensors

Train sensors are the signal input devices necessary for the operation of the control system.

H143: Broken sensors. If the sensors failed, failures would result in the control system, which poses a risk of critical severity. The probability of occurrence is occasional.

3.19 Environment

The environment of the hyperloop is everything that affects the system from outside, such as weather phenomena, electricity supply, internet supply, government regulations, nearby infrastructures and the nature surrounding the infrastructure, among others.

3.19.1 Physical factors

Physical factors include all weather phenomena that can negatively affect the system. The risks listed below should be foreseen a priori in the design phase of the system and when choosing the location, since both the probability of occurrence and the severity depend on it.

H144: Extreme weather. Weather conditions such as excessive heat could cause the tube to expand, which would have moderate consequences. The probability of occurrence is probable.

In addition, there are potential natural disasters that can have catastrophic and critical consequences.

H145: Earthquakes. H146: Floods. H147: Thunderbolts. H148: Storms.

Earthquakes and floods would cause the vehicle and the track to collide. Lightning could cause damage to the electrical system and storms could cause heavy objects to fall on the structure, causing in the same way the collision between the vehicle and the track or the interruption of the service. These risks are critical except for earthquakes that have been classified with catastrophic severity. The probability of occurrence is remote except for storms that are likely.

3.19.2 Electricity supply

H149: Electricity system failure. A failure in the power supply would cause the system to stop and the interruption of service. The consequences would be critical. The probability of occurrence is occasional but they are a redundant system and an emergency system would mitigate the risk down to a marginal severity.

3.19.3 Internet

The internet service encompasses the entire data cabling system and servers.

H150: System failure. It would affect the entire Hyperloop control system, the consequences would be critical and the probability of occurrence is remote.

3.19.4 Regulations

H151: Limitations of the hyperloop system. Governmental regulations, both national and international, condition the design and implementation of the service. Moreover, regulations that arise once the system is already in operation could result in the need to make changes to the system. These types of situations are not predictable and you should have enough time to conform to them, so they would pose a marginal risk. The probability of occurrence is occasional.

3.19.5 Human failures

H152: Terrorist attack. Among the human factors that can affect the system, terrorist attacks are one of them. They cannot be predicted and, although unlikely, they are catastrophic. The probability of occurrence is unlikely.

3.19.6 Nearby infrastructure

Nearby infrastructures can affect the system in terms of interference and vibrations.

H153: Interference with nearby infrastructures. In the event that such infrastructures existed before the Hyperloop implementation, the design would be done consistently with the existence

of such infrastructures and/or the contrary. Should Hyperloop system be affected by the nearby infrastructures, this would be a marginal risk and the probability of occurrence is remote.

3.19.7 Nature

H154: Natural environment encroachment. The hyperloop system could affect the environment around it due to electromagnetic emissions, vibrations, noise and the system's own occupation on site. It is a marginal risk that can be mitigated by making a previous study of the location of the system and adapting to it. The probability of occurrence is probable.

3.19.8 On-board propulsion

3.19.8.1 Axial compressor

This propulsion system is used by some hyperloop developments to maintain the high speeds during most of the journey, avoiding the use of LSM in the cruise phase. This component uses the air in front of the vehicle to generate thrust by compressing it, similarly to the first stages of an airplane engine without any fuel burning. This system, although it presents multiple benefits, such as simplicity of the infrastructure and lower costs, has an associated risk.

H155: fan ingestion. Foreign Object Debris (FOD) that is left or generated inside the tube can be ingested by the compressor, causing major damage to the system and potentially to the cabin. The FOD coming from the exterior is extremely unlikely given the closed environment of the Hyperloop infrastructure by nature. However, FOD coming from the interface are subject to fall within the tube. Hence, the probability of occurrence is taken as remote, level D, and the consequences as critical (level 2), since the propulsion system will be severely affected. This leads a level of risk of D2. To reduce this level of risk, a preventive maintenance strategy, with a strong focus on FOD has to be established, along with training of related personnel and regular inspection or the automation for detecting FOD within the tube. These measures, will potentially decrease the likelihood and severity of the even, resulting on E4 in the risk matrix.

3.20 Evacuation

One of the problems that has to be addressed regarding the infrastructure would be the evacuation procedures. Passenger safety is one of the key elements for the future development of the hyperloop.

Passenger safety concerns not only the integrity of the vehicle and infrastructure, but also the evacuation procedures to be followed in case of emergencies.

As has been seen in previous sections, knowledge of the regulations applicable in other areas such as railways and roads, and in particular tunnels, is of great help in determining these actions (**Table 15**).

Table 15 References

Reference	Description	Year
Directive 2004/54/EC	Minimum safety requirements for tunnels in the Trans-European Road Network	2004
Commission Regulation (EU) No 1300/2014 (TSI-PRM),	Technical Specifications for Interoperability, Personnel with reduced mobility	2014
Commission Regulation (EU) No 1303/2014	Technical Specifications for Interoperability (TSI), Safety in railway tunnels (SRT),	2014
Commission Regulation (EU) No 1302/2014 (TSI-LOC&PAS)	Technical Specifications for Interoperability, rolling stock - locomotives and passenger rolling stock,	2014

Generally speaking, it can be said that there must be control systems in place to detect an event against the safety of the hyperloop system. In this case, a safe stopping point or safety areas compatible with the infrastructure must be chosen (Figure 49).

Access to these points can be made in three ways:

- a) By means of the vehicle itself (Pod).

The pod must be able to reach the safe point by its own means or remote control or by means of an auxiliary propulsion system (e.g. a catenary). Passengers must be able to access the safe point with all accessibility guarantees (COMMISSION REGULATION (EU) No 1300/2014) and coordination with Civil Protection teams must be established to ensure evacuation or to be able to continue the journey.

The directive Technical Specifications for Interoperability, rolling stock - locomotives and passenger rolling stock, Commission Regulation (EU) No 1302/2014 (TSI-LOC&PAS) specifies the requirements for rolling stock in case of fire. This rolling stock must be designed to resist fire with running capability until it reaches a safe area.

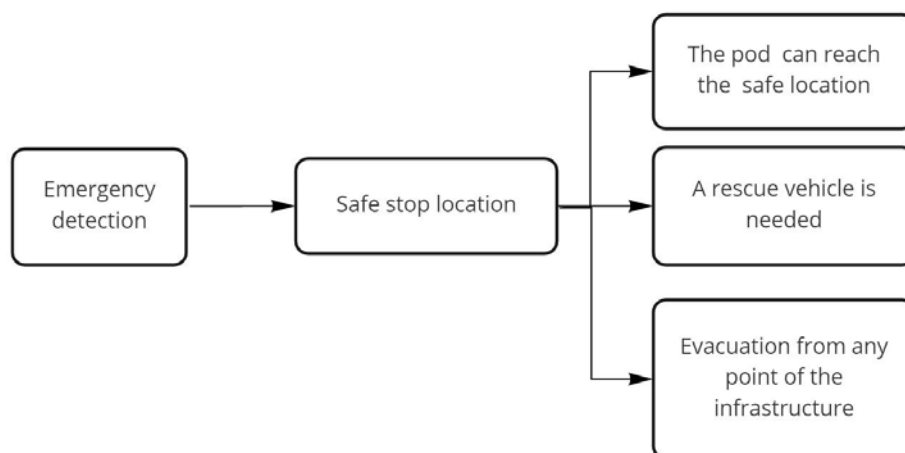


Figure 49 Types of access to safe points in case of an emergency

- b) Access with a rescue vehicle is required.

The rescue vehicle must be able to access the pod and passengers must be able to be safely transferred to rescue transport. The rescue vehicle will reach the safe point and coordination with Civil Protection will be established to proceed with the evacuation.

(c) Evacuation must proceed from any point on the infrastructure.

The infrastructure must have points accessible on foot. In accordance with the European directive on tunnel safety (Directive 2004/54/EC), these distances between emergency exits must not exceed 500 m and there must be emergency stations every 150 m, including a telephone and two fire extinguishers.

In addition, the hyperloop must have a vacuum control system and additionally have a system of personal protective equipment to be able to operate at different vacuum levels if necessary. The emergency doors of the hyperloop must be able to be opened when the vacuum and protective conditions require it.

Throughout the emergency, it must be ensured that the traffic management system manages the different vehicles circulating in the tunnels at the time of the emergency, diverting or stopping them when necessary.

Another aspect to consider is the need for permanent communication with pod passengers, as there are developments where the incorporation of cabin crew to accompany passengers is not being considered.

De acuerdo con The Technical Specifications for Interoperability (TSI), Safety in railway tunnels (SRT), Commission Regulation (EU) No 1303/2014 es preceptivo incluir safety areas en la construcción de los túneles y cita textualmente las siguientes propuestas si el túnel supera 1 km de longitud :

- *Lateral and/or vertical emergency exits to the surface. These exits shall be provided at least every 1 000 m.*
- *Cross-passages between adjacent independent tunnel tubes, which enable the adjacent tunnel tube to be employed as a safe area. Cross-passages shall be provided at least every 500 m.*
- *Alternative technical solutions providing a safe area with a minimum equivalent safety level are permitted. The equivalent level of safety for passengers and staff shall be demonstrated using the Common Safety Method on risk assessment. For information related to CSM, see ERA CSM*

Also it establishes the dimensions for escape walkway to the safe area with width of 1.5 m and height of 2.25 m. If the evacuation routes have a complex geometry like chicanes, bends,.. we have to increase the width and the height of the corridors to evacuate the passengers. The access doors to safe areas need 1.4 m wide and at least 2.00 m height and can be substituted with more doors with less width but with higher passenger evacuation capacity.

As for this transport layout, this evacuation risk could be similar to the case for railways evacuation on tunnels, with the main difference of, on first-hand, being the tunnel a low-pressure environment.

Some of these problems has been addressed at a research level, as on the paper *Evacuation of an Hyperloop pod in a long tunnel* (Narve Lyngby; Eivind Grøv; Thor Myklebust), in which European legislation is analysed regarding railways and aviation to evaluate how to create safety case method for this purpose.

Different solutions are presented of different studies regarding the quantity, separation and dimensions of escape routes in case of evacuation for different transport modes as we can see in Figure 50. The Malta-Gozo Tunnel is designed with safe lateral walkways (a) and for a subsea road tunnel SINTEF presents safe areas building with a sustainable material named FOAMROX. This is also a cheaper solution that build a lateral corridor in a tunnel like the Malta-Gozo tunnel. Instead of designing escape routes to go along the tubes, it is proposed to have different escape rooms in which the passenger can be allocated until the section of the tube inside the tunnel where they stopped can be accessed by the rescue team.

Inspired in these previous designs a hyperloop installation has been developed. It takes advantage of the space between the two tubes as seen in Figure 51.

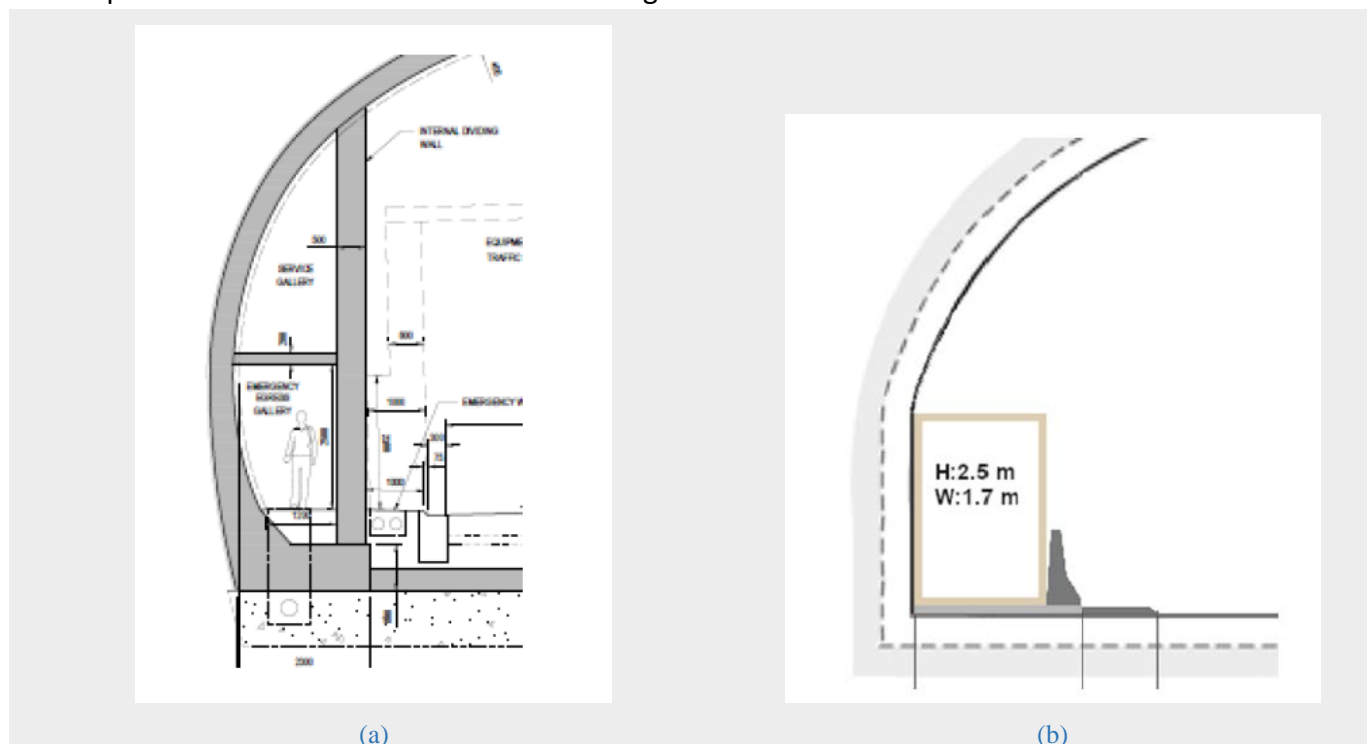


Figure 50 (a)concept solution for the Malta – Gozo tunnel prepared by COWI & SINTEF for Infrastructure Malta left, (b) A Foamrox concept for the Föglö tunnel på Åland courtesy by FS Links right.

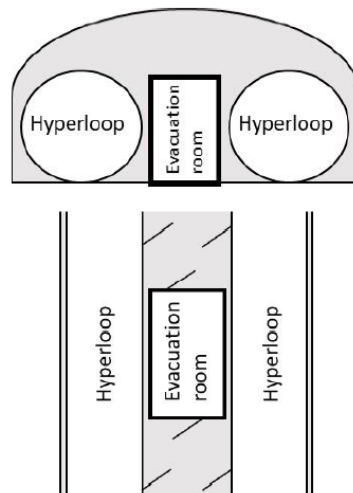


Figure 51 Stationary evacuation room, a waiting room, Evacuation of an Hyperloop pod in a long tunnel (Narve Lyngby; Eivind Grøv; Thor Myklebust),

For outside evacuation routes in which a tunnel is not involved and it is just the vehicle inside the infrastructure, on this paper it is proposed to have installed the infrastructure with 10km sections of what it is called Isolation Zone.

There would be a valve on each side of this sections to isolate the section where the vehicle stopped and pressurize it before passenger evacuation.

This paper is a good example of how to approach evacuation on hyperloop and it could lead to future studies on the matter such the system to ensure vacuum is over in the Isolated Zone before vehicle's door open or how to build some infrastructure's posts or columns with an emergency exit path, such as emergency stairs to evacuate passengers from elevated infrastructure.

Still more research about evacuation is needed but it is necessary to define the type of infrastructure, vehicles and communication and management systems to give adequate safety evacuation procedures.

3.21 Future research on hazard risk and safety case

The analysis of hazards and safety case have made it obvious that further research is of crucial importance. Below we have listed relevant topics to be developed in the future research activities and a short explanation about each one of them.

1. Technical Readiness Level. It is a big challenge if a system has a low TRL and a high SIL. E.g. a high-speed switch is at TRL4 today and should be SIL4 (like for railway). This is important for the first Hyperloop line that will include switches. Another is the gate valve. In addition, there will be very few suppliers of such systems.
2. Safety instrumented functions (SIS), their link to the design and how they work as safety barriers. And in addition, spurious trips could be dangerous.

3. Design, regulation and standardization are developing about instrumented systems and the research could be improved for the vehicle as a part of the tube.
4. SIL determination with the effect on it of Safety Instrumented Functions (SIF) from sensor to final element, variable depending on design, typology of line and context.
5. Development processes and related safety aspects, such as Agile, DevOps, SafeScrum etc.
6. Further safety analysis involving software, big data and Machine Learning and Artificial Intelligence techniques, depending on design, typology of line and context.
7. Machine Learning and Artificial Intelligence safety processes and how to integrate them into future functional safety standards (e.g. ISO/IEC draft TR 5469).
8. Electromagnetic compatibility inside a tube;
9. Relevant magnetic levitation aspects;
10. Safety cases and safety manuals as described in IEC 61508-2:2010 and IEC 61508-3:2010, to be improved in the next edition, and DIA, as described in ISO 26262-8:2018 and a security case as described in EN TS 50701. Maintenance of safety cases, including modules/items/products should also be looked into.
11. Valves: pressure and gate effects.

3.22 Conclusions on hazard identification and safety case approach

In this work, relevant hazards have been identified as part of safety analysis of a generic Hyperloop system. Several different domains have been evaluated to ensure completeness and the main focus has been on the railway domain. The different hazards have been identified, described and classified. Classification has been based on evaluations of probability and consequence.

A preliminary hazard log has been included, listing all the different hazards together with relevant mitigations and their matrix with class of risk. A list of 155 hazards has been recompiled including mitigation measures. The list of these hazards can be consulted in the Annexes.

A view on the safety case approach has been described, including relevant topics. The main emphasis has been on the railway domain, which has the most detailed description for the content of a safety case. Security case has become more relevant too. Standardization organization includes security cases in EN TS 50701:2021 for railway and ISO/SAE 21434:2021 for automotive.

Many challenges are still open and they represent wide fields to undergo further research, as synthetically described in §2.16.

4 Technical components of the Hyperloop architecture

4.1 Introduction

The task of this section work is to gather all the technical information available that will allow to gain knowledge on the various aspects of the Hyperloop from the safety and operational design of the system. The systems architecture need to be identified to show the building blocks of the system as well as possible vehicle designs. In addition comparison to railway architecture should be depicted as energy consumption of various implementations. Moreover, the applicability of current communication systems to Hyperloop, e.g. signalling systems, intelligent transport systems, autonomous vehicles and vehicle-to-vehicle communications, traffic management systems and similar need to be analysed.

Finally, innovative concepts for vehicle systems applicable to Hyperloop, railway and other guided transport modes need to be described.

4.2 Hyperloop infrastructure compared to other transport modes

In the following a comparison of Hyperloop with other transport, namely rail and aviation. This comparison is based on several parameters. The parameters are selected based on the analysis presented in (Van Goeverden, Milakis, Janic, Konings, 2018). The analysis is based on operational, financial and social/environmental performance, each with a set of parameters to determine the performance of Hyperloop compared to other transport modes (Figure 52).

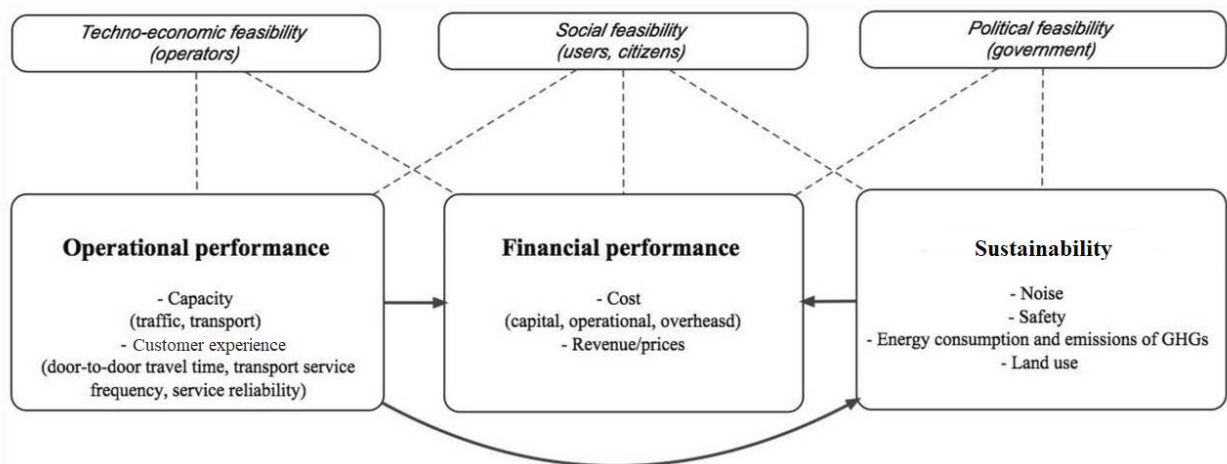


Figure 52. Analysis and modelling of performances of the hyperloop transport system. Source: (Van Goeverden, Milakis, Janic, Konings, 2018)

Furthermore, within the rail industry, there is a differentiation HSR and Maglev technology. The comparison for passenger transport is depicted in Table 15. The financial performance/cost of the Hyperloop infrastructure has been presented in Section 1. This comparison focuses on parameters related to operational and social/environmental performance.

Table 16 Comparison with other transport modes

	Aviation	HSR	Maglev	Hyperloop
Maximum speed (km/h)	600-925	250-350	300-600	500-1200
Commercial speed (km/h)	250-800	150-250 ⁴	249.5 (Single commercial line)	430-1000
Capacity per direction (passengers/h)	1363 ⁵ -2984 ⁶	6678 ⁷ - 28625 ⁸	2296 (Shanghai, 4 trains/hour)	810-123780 (estimations depending on the design and the number of vehicles per direction)
Urban integration	Airports need to be far away from city centers due to noise and gaseous pollution	Can use existing infrastructure to enter city centers	Vehicles and infrastructure not interoperable with HSR. Integration with other transport infrastructures needed.	Vehicles and infrastructure not interoperable with HSR. Integration with other transport infrastructures needed.
Energy efficiency	387 Wh/passenger/km ⁹	42-61 Wh/passenger/km ¹⁰	63 Wh/passenger/km @ 430 km/h	38 Wh/passenger/km @ 700 km/h
Cost effectiveness	Infrastructure shared by routes. Contribution to cost depending on number of operated flights	36 M EUR /km ¹¹ (European average)	121-159 M EUR/km ¹²	20-60 M EUR/km (report contributors estimation)
Resistance to external influences	Low Weather conditions or drone/bird strikes cause turbulence, crashes, inhibit	Medium Leaves or snow build-up, frozen switches, collisions with humans or	Medium Snow build-up, strong side winds affect the operations	High Enclosed tube environment

⁴ (European Court of Auditors, 2018)

⁵ Busiest domestic city pair: CJU-GMP (Official Aviation Guide, 2020)

⁶ Busiest international city pair: HKG-TPE. (Official Aviation Guide, 2020)

⁷ Busiest European HSR corridor: Paris-Lyon (Civity Management Consultants, 2013)

⁸ (Central Japan Railway Company, 2016)

⁹ (National Academy of Sciences, 2016)

¹⁰ (Frits, 2018), (Álvarez, 2010)

¹¹ (PwC, 2016)

¹² (Heller, 2008), (Lazo, 2018)

	Aviation	HSR	Maglev	Hyperloop
	take-off/landing, causing delays and cancellations	vehicles ¹³ at level crossings affect the operation		
Connections between stations	Direct connections	Slow down and stop for intermediate stations	Slow down and stop for intermediate stations	Direct connections
Distance between destinations (km)	> 2000 (medium-long range)	500-600	800-1000	50-2000
Headways (min)	1-5 (between take-offs)	> 2.5 (European Commission, 2008)	> 2.5	0.02 – 2.5 (depending on the technology)

Hyperloop performs particularly well compared to the other transport modes in terms of its flexibility, being able to offer short departure intervals at high speed, while providing high capacity. Moreover, hyperloop is able to offer a high capacity and at the same time have it easily adjusted depending on the current need by either increasing or decreasing the speed. One of the main attributes of Hyperloop is its energy-efficiency, enabled by the low-pressure environment that reduces and eliminates air friction for the vehicles. The system comprises a fully enclosed tube that protects the infrastructure from external influences, reducing maintenance needs and decreasing operational expenses. Nevertheless, the construction of a new ground infrastructure is needed. Furthermore, this new infrastructure must be integrated into current and future spatial planning policies. The multimodal connection of the Hyperloop with other transportation modes and their networks, e.g. for rail stations, airports, etc., is an area that requires further research and analysis. The research should also include comparison to road for cargo transport as well as to comparison with electric car/buses for passenger transport.

4.3 System Architecture

Currently, different Hyperloop developers are working on their own systems. Each approach differs in the systems' architecture and subsystem components, better defined in §1.2.2 and §1.2.3.

Yet, there are several steps taken towards reaching consensus on systems architecture, mainly utilizing the system engineering principles.

There are two important developments towards convergence:

- An industry wide consensus on the functional breakdown of the hyperloop [S2RHL. 2021]¹⁴;

¹³ Usually, HSR routes have level crossings only at legacy sections near cities. Newly-built dedicated lines do not cross existing infrastructure

¹⁴ This work has been facilitated by the DG MOVE/S2R hyperloop promoters group

- The European Standardization Technical Committee CEN-CENELEC/JTC 20 *Hyperloop systems* has started the drafting work on 5 work item, one of them in particular looking into the system building blocks (Figure 53).

The agreed industry wide functional breakdown of the hyperloop is organized into functions related to infrastructure, vehicle and control and operating system (Figures 53 and 54).

The Hyperloop system design is a clean-sheet problem, namely there are no legacy systems to take into account being dependent on the laws of physics, economics and human psychology. For each function there may be various system designs and implementations.

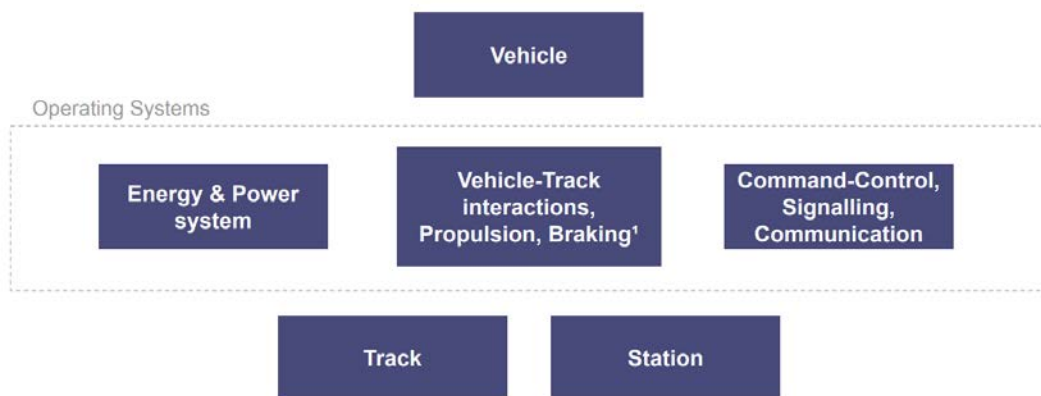


Figure 53. Hyperloop reference architecture currently under development at JTC20

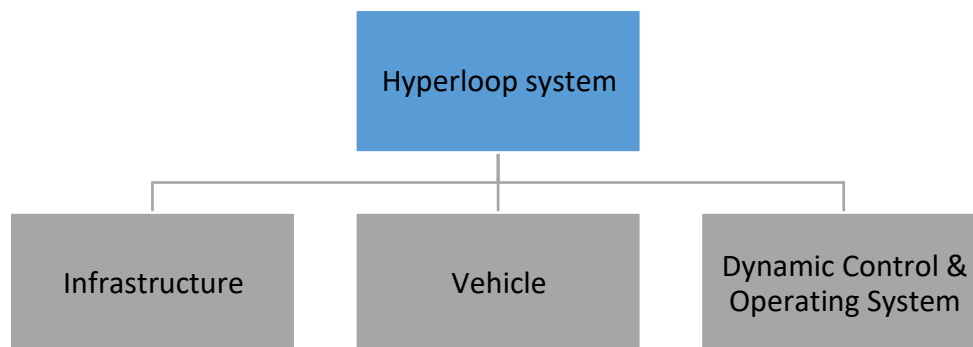


Figure 54. Functional breakdown of the hyperloop system

Hyperloop system invokes many engineering disciplines including structures, electronics, aerodynamics, electromagnetics, thermodynamics, controls, manufacturing and civil engineering. As shown in (AECOM, 2020) all these disciplines are interleaved in the system, subsystem design.

The following sections describe the system components as well as some of the possible designs and implementations of the subsystems. In addition some of the parameters, such as acceleration parameters that need to be taken into account in the design of the systems and subsystems are given.

4.4 Infrastructure

The hyperloop infrastructure comprises of tubes that allows for vehicle travels in an enclosed, low-pressure environment.

From a functional perspective infrastructure could consist of:

- Track structure and enclosure;
- Low pressure environment control;
- Stations and track infrastructure to support them.

The enclosed pathway is able to withstand:

- Applied forces caused by the vehicles travelling inside, including static and dynamic loads from the longitudinal and transversal forcing systems;
- Applied forces caused by the infrastructure itself, including static and dynamic loads from the weight of the infrastructure, thermal expansion and contraction and air pressure differential, including those to prevent collapse due to buckling;
- Environmental factors within planned limits, including sunlight, temperature gradients, wind, storms, precipitation or earthquakes;
- Resistance to environmental factors such as extreme weather conditions, earthquakes or other intentional hazards (malicious acts, sabotages, cyber threats, etc.).

4.4.1 Infrastructure subcomponents

The subcomponents of the infrastructure can be grouped into two main parts:

- The tube itself and its internal components, generally known as superstructure;
- The support and the required foundation generally known as substructure.

A proposal of these components is illustrated in Figure 55.

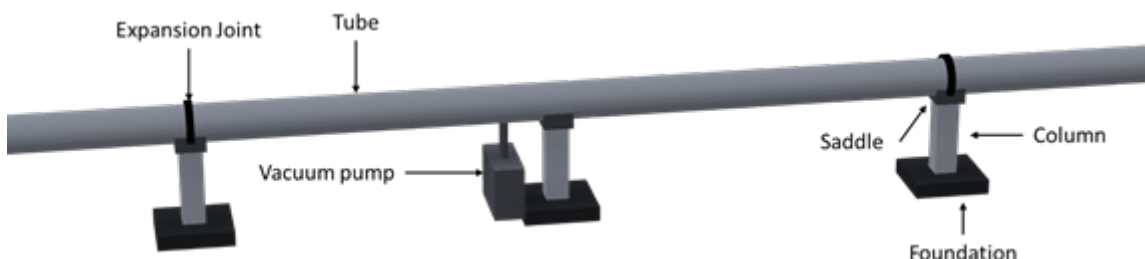


Figure 55. Example of the schematic view of the a hyperloop substructure and superstructure

The superstructure comprises the tubes, the expansion joints, the switches, and the low-pressure environment control. Switches are necessary for movement of the vehicles from one tube to another one enabling change of direction to stations, other tracks/destinations or movement to the maintenance area. Switches are considered as mandatory by some hyperloop developers, while for others they are optional.

The superstructure is supported onto the ground by means of a substructure. The substructure contains a saddle, where the expansion joint lays on the column, the column itself and a foundation. The design of the sub-structure is highly dependent on soil characteristics, the exact location and other externalities, but it must be built at strict tolerances in order to allow the vehicle to reach high speeds. Each of these components will be discussed in the following subsections.

4.4.2 Tube sections

The tubes are one of the larger components of the Hyperloop infrastructure. As such, they are also one of the main cost drivers. An optimized design of the tubes will help reduce overall implementation costs and improved material characteristics can lead to a more efficient system configuration, also helping to reduce the cost.

There are various material alternatives, each with its own advantages and disadvantages.

A study conducted by (Delft Hyperloop, 2019) compared several materials such as concrete, steel, aluminium and acrylic. The paper concludes that, among these materials, steel was the best option in the conditions of the study. This comparison considered aspects, such as costs, span suitability, thermal expansion, workability and airtightness. Using, for example, structural steel of the type S355M J2 for the tubes would strike a compromise between cost efficiency and other qualities, such as strength, stiffness, imperviousness to most gases, welding easiness and availability. However, to determine the most suitable type of pipe, the tube assembly process and environmental aspects must be considered as well.

Other factors that can contribute to reduce costs and construction time are the manufacturing of the tubes themselves and the on-site construction. In this regard, the Universidad Politécnica de Valencia recently presented its *Tubeloop* technology for the construction and manufacturing of hyperloop infrastructure elements. *Tubeloop* is a novel tube manufacturing and assembly method that will facilitate hyperloop infrastructure scalability by accelerating route deployment processes while reducing construction costs. Tubes are made of a composite material that consists of three layers: the inner and outer layer use fibre materials providing resistance, while the core layer in between consists of a polymeric or cement-based foam in order to thermal and acoustic isolation properties.

The manufacturing of the tube is simplified and fully automatic: firstly, the inner and outer fibre layers are created at the factory. Then, after a chemical reaction, the inner core is incorporated. Lastly, valves, globes and vacuum bags are added. The result is a structure that can be folded for ease of transportation (Figure 56). This novel technique allows a truck to transport dozens of tubes wound on a coil at the same time. The flat tubes are inflated in situ. Consequently, transport costs and carbon footprint can be significantly reduced.



Figure 56: Tubelooop concept for hyperloop infrastructure

In order to gain insights and testing manufacturability, (semi-)automation, reachable tolerances and thermal expansion of the test track, Mercon has built a prototype of the infrastructure in Groningen¹⁵ (Figure 57).



Figure 57. Manufacturing tube process (above). Source: Mercon. Infrastructure prototype at the EHC site in Groningen (below). Source: HARDT

4.4.2.1 Tube diameter and wall thickness

The diameter of the tube needs to be carefully designed, such that it fits the purpose of the type of services to be provided by the Hyperloop, namely transporting passengers, cargo or both. In addition, some requirements may be imposed by the environment or physics laws for vehicles traveling at high speeds in enclosed environments (*Kantrowitz* limit). Currently there is no

¹⁵ [Infrastructure prototype EHC](#)

agreement within the industry on the optimum measurements of the diameter but this is an urgent issue to prevent future interoperability problems from the very beginning..

Another important parameter of the tube is its wall thickness. It is a parameter that directly influences the statics and dynamics of the pipe, its buckling behaviour and ultimately the cost. For designing the tube to withstand the low-pressure environment, the stresses in the material must stay under a certain limit to be safe. Several existing European standards are deemed as basis for tube design:

- The European standard EN13445 and its series that provides guidance for the design of the pressure vessel: this standard dictates the thickness of the tube and the amount of radial stiffener rings for pressured vessels, it minimizes the risks and ensures safety when scaling; some deviations from the calculations are also allowed, provided that different components can be loaded without exceeding allowable stresses in materials;
- The Eurocode standards and the EN 10219-2 (Cold formed welded steel structural hollow sections – Part 2: Tolerances, dimensions and sectional properties).

Overall, the lower the operating pressure, the higher the tube requirements in terms of stress and tolerances and the higher its manufacturing costs.

Research is needed to analyse the linear and non-linear static, dynamic and buckling behaviour of the pipes considering all relevant load cases during construction and operations of the Hyperloop. Moreover, further testing and research is needed to decide on the optimum diameter size of the tube.

4.4.3 Expansion Joints

One of the concerns often raised regarding the hyperloop is the total expansion of the tubes in the hyperloop infrastructure. As indicated in (Museros, Lázaro, Pinazo, Monleón, 2021) stresses due to thermal expansion were, by far, the highest and their magnitude is independent of the section properties. A possible solution is to adapt existing solutions of deploying the expansion joints consisting of metal bellows.

One factor that defines the interval distance of expansion joints is the expansion/compression of each expansion joint and what is acceptable in terms of gap between the tracks. Other factors are local vs. uniform expansion, joint stiffness or joint leakage.

(Museros, Lázaro, Pinazo, Monleón, 2021) studied the design constraints of tubular steel viaducts for Hyperloop. They propose two basic configurations to deal with thermal expansion: a tube jointed to the piers and a tube not jointed to the piers that can freely expand (Figure 58). They consider steel S460, according to Eurocode loads. They conclude that long structures (hundreds of km) with no expansion joints and no restrictions to expansion would have longitudinal displacements of the order of magnitude of the span length, which would require the development of non-standard technological solutions for supports on piers and stations. For the tube jointed to the piers structure, a case is studied with a span of 28 m and 25 mm thickness under the Eurocode

loads to check the orders of magnitude of the effects of different actions. Thermal expansion imposes highest stresses regardless of the section properties.

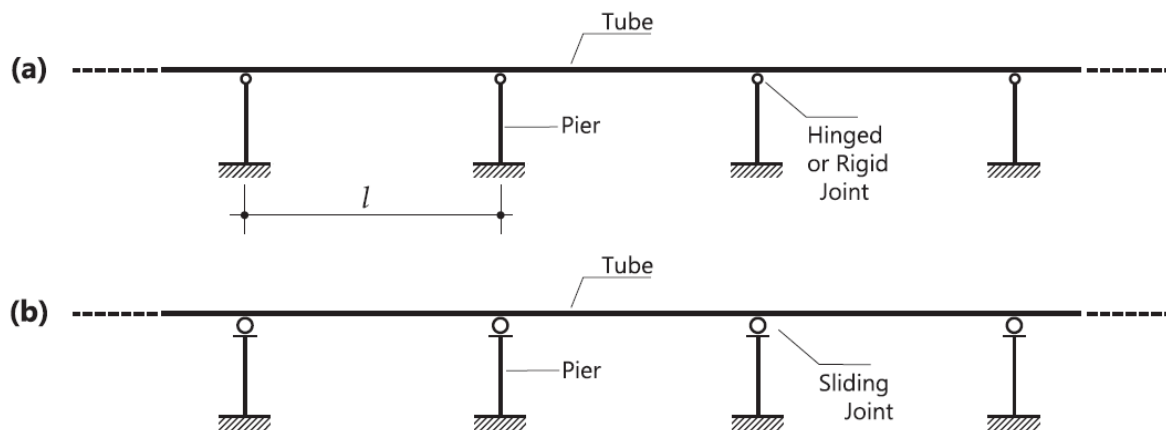


Figure 58. Structural systems for hyperloop viaducts of span length l in R-Configuration (restrained axial expansion) (a) and F-Configuration (free axial expansion) (b). Source: (Museros, Lázaro, Pinazo, Monleón, 2021)

4.4.4 Tracks

The infrastructure consists of tracks that enable levitation, a guidance and the propulsion of the vehicle. The vehicle-infrastructure interface tracks is already introduced HYPERNEX D2.1. In this section, more details are given on each solution.

The functionality of the tracks differs among the Hyperloop concepts currently under development. Therefore, depending on them, the interfaces inside the tube widely vary. The two main variants are: vehicle-based propulsion and infrastructure-based side propulsion.

The design and dimensions of the tracks are mainly dependent on the requirements from the magnet and vehicle design. In the design of the tracks the dynamic effects, as well as excitation of the tube and interaction with the magnetic mechanisms used need to be taken into account.

The tracks consist of separate segments attached to the tube. Just like the tube, the tracks will be subjected to thermal expansion. A solution to overcome thermal expansion could be to separate track segments with a small gap. The length of the tracks is dependent from the static/dynamic requirements as well as their manufacturability.

4.4.5 Switches

Switches in railways are a vital part of the infrastructure and the network. They enable flexibility in terms of operations by allowing the operators at guiding the trains from one track to another one, as well as capacity increase and efficiency in terms of scheduling for both passengers and cargo transport. In addition, the rolling stock can be guided to maintenance yards when necessary. Similarly switching in Hyperloop will enable flexibility in operations, divergence to destination stations without impacting the traffic flow, as well as provide with means to perform maintenance

without impacting the traffic, especially in case of emergency repairs. Switching will also enable high capacity in Hyperloop (Mendes Borges, Quaglietta, 2021).

Current Maglev systems, for example, either operate only point-to-point routes or require mechanical switches for the connection to other network nodes. These mechanical switches force the vehicles to slow down, adding cost and complexity to the infrastructure, and increase maintenance costs due to moving parts. Figure 59 shows a guideway switch of a Maglev system in Shanghai. The dark grey segment of the track is composed of multiple parts that move the vehicles towards the different platforms.

Although these switches have proven to be reliable thanks to the redundancy in the control system as failure mode mitigation strategy, their operation requires a speed reduction to 100 km/h.



Figure 59. Transrapid guideway switch in Shanghai.

4.4.6 Hyperloop Switch

The switch lay-out designed for hyperloop and tested at low speeds at the low-speed test facility in Delft is a different approach compared to other high-speed, ground-based transport, such as high-speed rail (Figure 60).



Figure 60. Low-speed test facility in Delft (above). Source: HARDT. Virgin Hyperloop One's facility in Nevada (below). Source: Virgin Hyperloop.

The low-speed switch tested by HARDT in Delft enables infrastructure that operates without these mechanical switches and it is achieved by means of electromagnetic forces, which require no mechanical components or moving parts. This magnetic switch is intended to operate continuously with no interruptions, potentially giving the infrastructure the ability to handle multiple vehicles per second (Mendes Borges, Quaglietta, 2021). This does not imply that the network will operate at this frequency, it merely describes the capability of the high-speed switch. *Virgin Hyperloop One* has recently presented utilization of the high-speed switching in their new concept.

The switch tested at the low-speed test facility in Delft works such that the vehicle guideways consists of levitation and guidance tracks to allow for en-route switching. The first is used to

levitate the vehicle, while the latter are used for stabilizing the vehicle and keeping it on track. An example of a switching mechanism consists of a guidance track on each side of the vehicle. When the vehicle needs to change track the switch will engage it. Using one guidance track, the vehicle is pulled towards the splitting line (Figure 61, functional, not in scale). For example, when the vehicle is guided towards the secondary track, it pulls itself towards it using the right (red) guidance track. And when it is guided to go straight, it continues along the (green) track.

When splitting (blue path) the vehicle from the straight (yellow path), the right guidance (red) track pulls the vehicle through the curve. During the switch, stability is guaranteed by centrifugal forces and the inner guidance track. When going straight, stability is guaranteed by pulling towards the left using the straight guidance (green) track.

The speed at which a vehicle diverges from its straight path, is mostly limited by human comfort requirements, which requires lateral accelerations under 0.2 g and a the maximum variation of acceleration (jerk) to be under 0.3 g/s (Hoberock, 1976) (Maglev Technical Committee, 2007), This, in conjunction with the smoothness of the transition from straight line to curve, namely the change and the minimum curvature, limits how fast the vehicle can run under the maximum cornering forces. Testing of the high-speed switch is planned at the *European Hyperloop Center* (EHC) in Groningen, the Netherlands, currently under development.

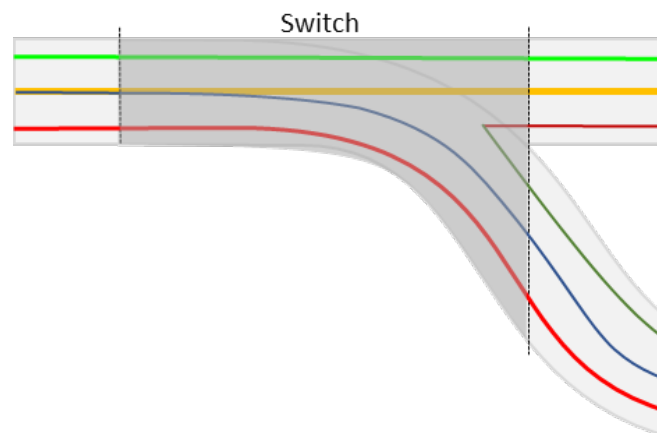


Figure 61. Example of Hyperloop's switch concept. Source: HARDT

4.4.7 Substructure

The supports are the connection between the tube and the soil. Raised above ground by the columns, the tube rests on the saddles. The foundation is the base of everything, creating a stable foot resting on the soil. Depending on the type of soil, a different kind of support might be required. This is a well-developed area. Various types of existing infrastructure have been designed with similar components, like bridges or guideways for cars, trains, pedestrians in sizes similar or much bigger than the Hyperloop guideway.

One factor that will need to be determined for Hyperloop is the number of supports per km needed. These depend on the necessary distance between them, known as span. This span defines the total deflection (sag) of the infrastructure and stresses in its material. This deflection is

important for straightness and alignment of the track. Furthermore, the dynamical effects, natural resonance frequencies need to be considered. The relationship between natural resonance frequencies and span lengths for a collection of rail bridges is depicted in Figure 62. Further research analysis is necessary to determine the balance between total deflection and dynamical behaviour, specifically for Hyperloop.

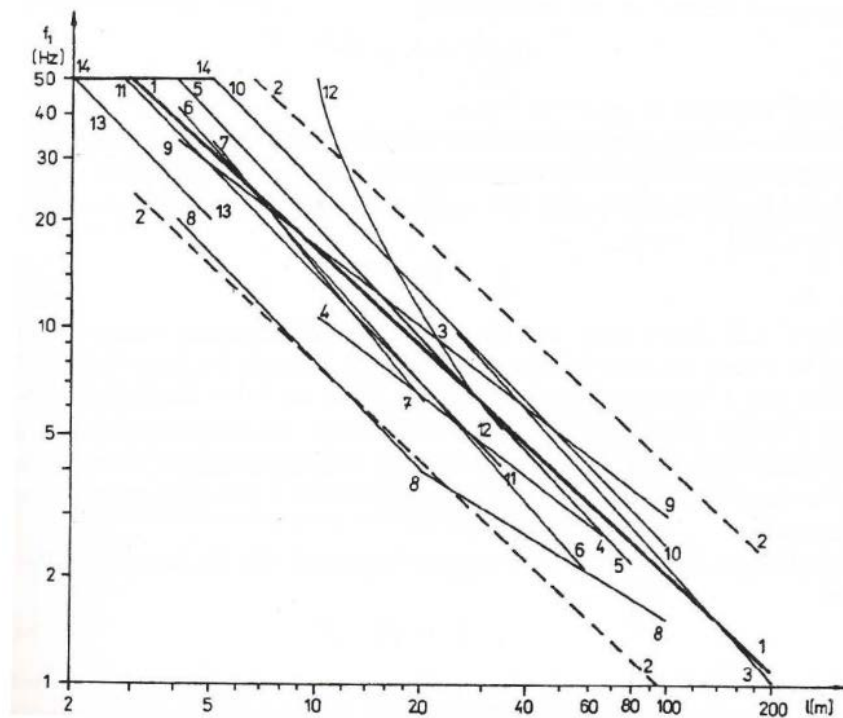


Figure 62. First natural frequency plotted against span length for a collection of rail bridges.

Source: Mellier

4.4.8 Low-Pressure Environment Control

The main functions of the subsystems in low-pressure environment are:

- To reduce the pressure in the enclosure below atmospheric pressure, to prepare for beginning vehicle operations after a period of time, when the enclosure's pressure has been elevated;
- To maintain the reduced pressure, by eliminating gases introduced into the enclosure over time, including air from outside, which leaks into the enclosure, air (or other gases) from the vehicles, which leak into the enclosure and outgassing produced by infrastructure and vehicles;
- To control pressure in enclosure, as required during each operational phase.

4.4.8.1 Vacuum Pumps

The Hyperloop has a low operating pressure inside the tube (Figure 63). For pumping down the tube, a vacuum system must be installed to get to the ultimate pressure within a reasonable time-period. Thereafter the operating pressure should be maintained.

It can be assumed that the tube will not be entirely airtight: given the sheer size, there are many welds, inlets and outlets of cables, expansion joints and others. The total amount of air scales with diameter squared, while the leaks scale linearly with the diameter.

The pump stations can be installed at a certain interval to pump down the infrastructure, and keep it at the right operating pressure. Establishing the optimal operating pressure is a subject study and testing for all Hyperloop developers as well as for the Hyperloop research community. Several publications refer to different values such as:



Figure 63. Vacuum system for testing purposes. Source: Universidad Politécnica de Valencia

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1. According to (Delft Hyperloop, 2019), the optimum pressure depends on the vehicle frequency (Figure 64);
2. According to (Tudor, Palone, 2021), a framework is proposed that allows to determine the optimal pressure within the tube depending on the length of the track. For example for a length of 1000 km the optimum pressure inside the tube would be 1.14-17.25 mbar (0.11-1.72 kPa), while for a length of 226 km it would be 1.17-54.40 mbar (0.12-5.44 kPa).
3. It must be noted that these studies do not take into account the Hyperloop concepts utilizing a compressor. For this concept (Bao, Hu, Wang, Ma, Rao, Deng, 2020) (Zhang, Jiang, Li, 2020) (Lluesma Rodríguez, González, Hoyas, 2021), [Zhang 2020] use as optimum 0.1-0.2 atm (10-20 kPa).
4. Further research is needed to derive the optimum pressure for hyperloop taking into account all aspects of the hyperloop system, among different hyperloop concepts depicted in HYPERNEX D2.1. The pump-

down time is also affected by internal pressure. Lower internal pressure could potentially cause longer pumping times and higher energy usage. On the other hand, lower internal pressure causes lower aerodynamic drag and hence lower energy consumption and higher speed of the vehicle.

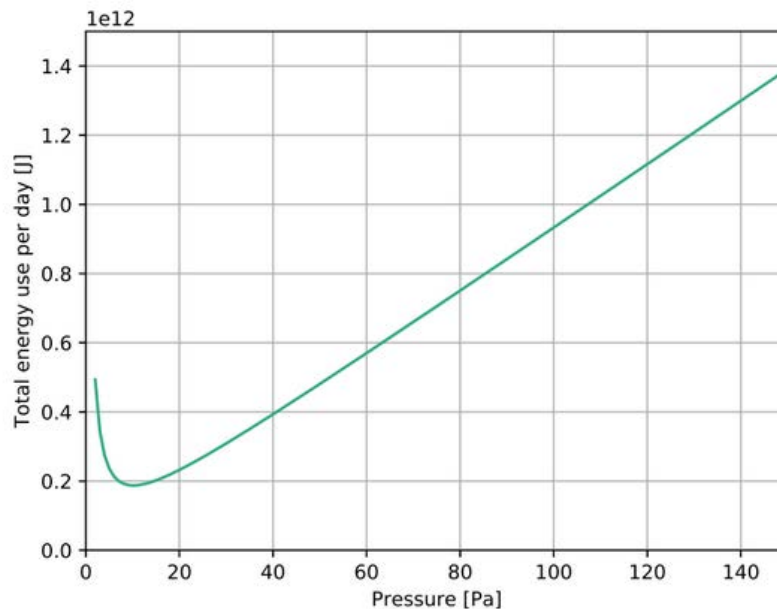


Figure 64. Energy consumption for vacuum pumps and overcoming aerodynamic drag for different operating pressures with frequency of 12 vehicles/h. Source: Delft Hyperloop, 2019

4.4.9 Infrastructure implementation examples

Various implementations of the infrastructure are possible (see Figure 65). The tubes are either elevated on columns above ground, on ground level, or underground. Each implementation type has its advantages and disadvantages.

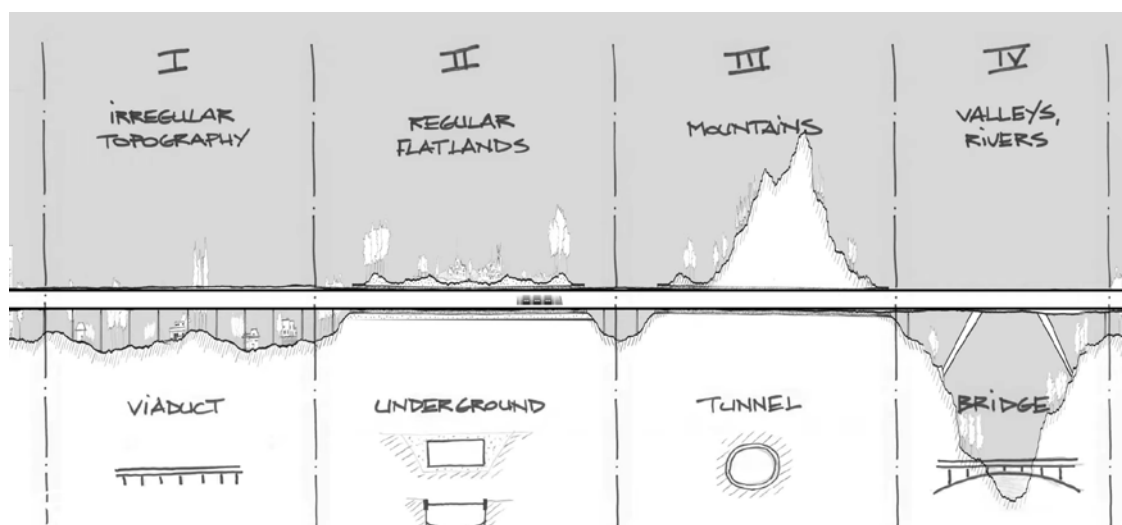


Figure 65. Infrastructure implementation methods. Source: Fhecor & Zeleros

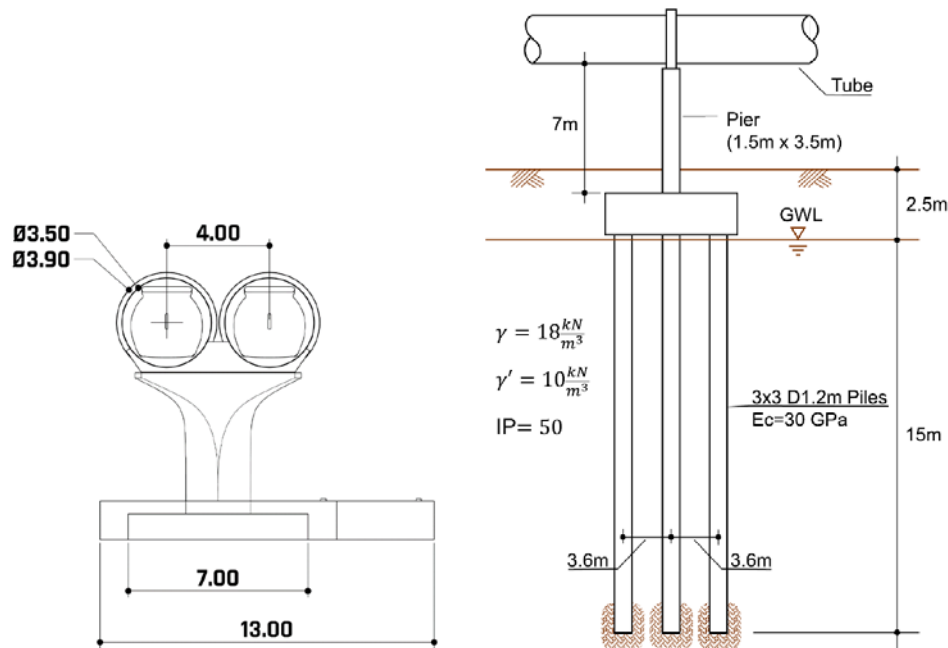


Figure 66. Examples of Hyperloop elevated infrastructure (Evacuation systems are not represented). Source (right): (Museros, Lázaro, Pinazo, Monleón, 2021)

An example of a basic construction solution above the ground consists of a foundation, column, column head and the tubes are depicted in Figure 66.

For the tunnel infrastructure, one possible implementation is utilizing the conventional method of placing both Hyperloop tubes inside a single tunnel including space for inspection and assembly (Figure 67). The extra space is 1 m around the tubes, with an inner diameter of the tunnel of 10 m.

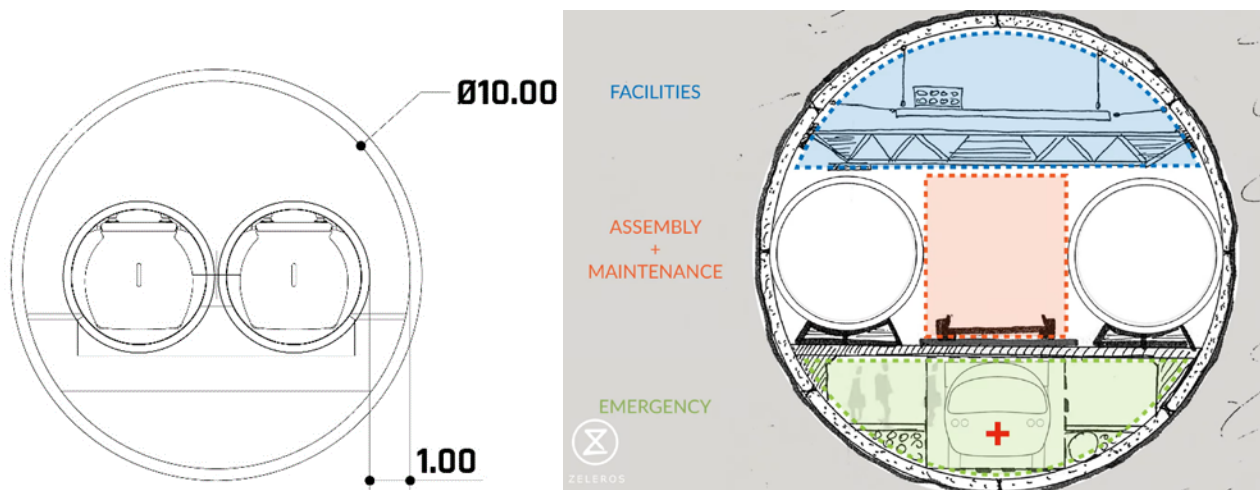


Figure 67. Examples of possible cross sections of underground hyperloop tunnel with conventional building techniques. Source (right): Zeleros

Underground implementation has the lowest impact on the environment and is most resistant to outside interference. The downside is the much larger cost than above ground implementation.

The lowest cost option in terms of materials required is to place the tube directly on the ground, but this solution has the highest impact on the environment and can be more affected by earthquakes, flooding and other natural disasters. Therefore, the most advantageous solution is an infrastructure elevated on columns. This way, the infrastructure has minimum footprint and can be more easily integrated into existing infrastructure and spatial planning.

Smaller and alternative tunnel infrastructures that would reduce impact to the environment while simultaneously reducing the overall costs can be advantageous in certain situations and require further research. This type of tunnel can be seen as an alternative to connect certain cities, access city centres and/or facilities; e.g. to build an underground hyperloop station under an existing airport or railway station: in a proposed Hyperloop connection in Norway between the city of Trondheim and the Gardermoen international airport outside Oslo was suggested that 230/414 km (56%) will be in tunnels (Lyngby, Grøv, Myklebust, 2020).

4.5 Vehicle

The main components of the Hyperloop vehicle based on its functions are:

- Structure;
- Internal Environment.

An overview of the vehicle and its component is already provided in HYPERNEX D2.1, which is here recalled and detailed for some of the aspects.

4.5.1 Structure

The main structure of the vehicles is a pressurized chassis. Its main functions are:

- To carry static and dynamic forces between all vehicle contents and the longitudinal and transverse forcing systems;
- To withstand air pressure differentials between inside and outside the vehicle;
- To secure passengers and/or secure cargo;
- To provide mechanical mounting for all vehicle systems;
- To perform aerodynamic functions.

The vehicles designed for test purposes differ from the envisaged, future commercial Hyperloop vehicles. Depending on the chosen approach, the differences can lie in the shape of the chassis, the operating pressure, the scale of the vehicle, the number of passengers carried and/or other factors.

For example, the chassis of the main cabin used in the low speed test facility in Delft is composed of aluminum beams designed to have a certain weight and strength as well as vertical poles where additional deadweight can be added to simulate different vehicle operating conditions (e.g. half weight, full weight, unbalances between left and right side, etc. Furthermore, the chassis design of the test vehicle in Delft took into consideration space for batteries, suspension system and other electronic components (cables, sensors, electronic boxes, etc.).

Virgin's testing vehicle, on the other hand, has a 1:1 scale and can carry up to four passengers at speeds of up to 173 km/h and a 100 mbar (10 kPa) pressure. This vehicle may differ in the number of carried passengers with future commercial hyperloop solutions.

4.5.2 Vehicle internal environment

The design of the vehicle interior need to take into account the transport services to be provided, namely transporting passengers and/or cargo (Figure 68). The functions to be provided by the vehicle internal environment are:

- Accommodation for passengers, luggage and/or cargo;
- Air pressure, quality/composition, temperature and humidity control;
- Interior lighting;
- Protection of passengers and/or cargo from excessive loads, forces, impacts, motions, collisions, noises, vibrations, electromagnetic emissions;
- Reduction of noise and vibrations to increase passenger comfort;
- Additional accommodations for passengers, such as lavatories, entertainment and provisions for service crew;
- Oxygen supply and/or other means of life support during an emergency: aviation-pressure Hyperloop could use standard aviation oxygen masks during a depressurisation event;
- Other emergency systems (fire extinguishing equipment, redundant communication systems, etc.), as required by future Hyperloop safety regulations.



Figure 68: Hyperloop's vehicles used in test tracks or proposed by the developers

Cargo vehicles or prototype test vehicles not designed to carry passengers and without certain features may be created depending on the chosen approach (Figure 69).



Figure 69: passenger and cargo vehicles. Source: Zeleros (left) and Virgin hyperloop (right)

4.5.2.1 Acceleration and passenger comfort

The human body tolerance to acceleration depends on the direction and the duration of the exposure. During normal operations, the accelerations are kept in a comfortable range like those familiar from trains and airplanes. In case of an emergency, in which the vehicle must stop as quick as possible, a higher acceleration can be tolerated for a short period of time, just like having an emergency brake with a car or a train during an emergency braking manoeuvre. An example of established railway acceleration parameters that could be used for the design of a Hyperloop system are shown in the Table 17.

Table 17 Current established acceleration and deceleration parameters usable for a Hyperloop system. Source: (Eisenbahn Bundesamt, 2007)

Parameter	Value
Nominal start-up and brake related longitudinal acceleration (g)	0.15
Nominal lateral acceleration (g)	0.15
Nominal longitudinal jerk (g/s)	0.10
Emergency braking (argumentative) (g)	1.20
Vertical acceleration (crown/trough) (g)	0.06-0.12

4.5.2.2 Nominal accelerations

The design principles for Maglev established by (Eisenbahn Bundesamt, 2007) can be used as baseline values for Hyperloop. These values well correspond with values from studies, although the longitudinal accelerations are lower than what is currently acceptable for automotive and aviation. According to a longitudinal acceleration comfort study performed by the Department of Transport of the city of Washington (Hoerock, 1976) for public mass transportation, steady non-emergency accelerations in the range of 0.11-0.15g, falling in the acceptable range for most of the studies conducted. It is unlikely that values of jerk larger than 0.30 g/s would be acceptable for most public transport systems. During the studies, none of the acceleration values for public ground transport systems, in which passengers may be standing, exceed 0.16 g. On the other hand, if a passenger is properly seated (car or airplane) or prepared (motorcycle) the acceleration levels

can reach 0.6 g, such as in Figure 70 from (Lever, 1998) and (Lauriks, Evans, Förstberg, Balli, Barron de Angoit, 2003).

	<i>Design goal</i>	<i>Minimum requirements</i>	<i>Seated–belted</i>
<i>Lateral curves</i>			
Bank angle (deg)	24	30	45
Roll rate (deg/s)	5		10
Lateral (g's)	0.1	0.16	0.2
Roll acceleration (deg/s ²)	15		
<i>Vertical curves</i>			
Vertical (up) (g's)	0.05	0.1	0.1
Vertical (down) (g's)	0.2	0.3	0.4
<i>Acceleration and braking</i>			
Normal (g's)	0.16	0.2	0.6
<i>Vector combinations</i>			
Lateral/longitudinal (g's)	0.2	0.3	0.6
Lateral/vertical (g's)	0.2	0.3	0.4
Total (g's)	0.24	0.36	0.6
<i>Jerk (g's/s filtered at 0.3 Hz) or Jolt (peak to peak g's in 1 s)</i>			
Lateral	0.07	0.25	0.25
Vertical	0.1	0.3	0.3
Longitudinal	0.07	0.25	0.25

1 International and European ride comfort standards

Guidance according to ISO 2631-1		CEN (ENV 12299)	
Less than 0.0315 m/s ²	not uncomfortable	Less than 0,17 m/s ²	Very comfortable
0.0315 to 0.63 m/s ²	a little uncomfortable	0.17 to 0,33 m/s ²	Comfortable
0.5 to 1 m/s ²	fairly uncomfortable	0.33 to 0,50 m/s ²	Medium
0.8 to 1.6 m/s ²	uncomfortable	0.5 to 0,67 m/s ²	Uncomfortable
1.25 to 2.5 m/s ²	very uncomfortable	0.67 to 0,83 m/s ²	Very uncomfortable
Greater than 2 m/s ²	extremely uncomfortable		

Figure 70. Ride comfort guidelines for US maglev systems (up) and UIC comfort test (below)

The expectation is that the experience of a user within the Hyperloop vehicle is similar to the passenger experience in a commercial aircraft. Just like an aircraft, the rounded shape of the Hyperloop vehicle allows for equal distribution of the forces from the internal pressure.

4.5.2.3 Emergency braking acceleration

In general, human tolerance to gravitational/inertial forces in the longitudinal direction are much higher than other axes. This makes it possible to decelerate safely at a high rate during an emergency. According NASA experiences, deceleration of 2 g is tolerable up to 24 h under very specific conditions. This value is just a reference, as well as the value of 1.2 g adopted in automotive field for high-performance automobile for competition purposes. Basing on these experiences, such values could be acceptable for passengers in case of an emergency only, provided they are properly seated or secured. Anyway, further research and testing is needed in order to determine

the parameters specific to Hyperloop. Depending on the outcomes of such research it will be determined the acceleration and the possible need of seat belts as in the airplane.

4.6 Dynamic control and operation of the system

The main functionalities of this system and its subsystems are:

- To provide for longitudinal and transversal forcing of the vehicle;
- To accelerate and decelerate the vehicle;
- To counteract drag forces on the vehicle;
- To maintain the vehicle speed during coasting phases;
- To hold the vehicle in a stopped position;
- To manage linear motor with stator mounted to infrastructure or vehicle;
- To manage aerodynamic equipment (e.g. compressors);
- To combine or separate propulsion and braking systems, with optional regenerative braking;
- To check track or guideway.

The subsystems' design and functionality are highly dependent on the chosen implementation. The various implementation of the magnetic levitation/guidance/propulsion system to work are depicted in HYPERNEX D2.1. Several technologies are currently being developed and tested. Further research and in particular prototyping and high-speed testing is necessary to determine the best performing technologies.

4.6.1 Levitation and guidance

The general reference is to HYPERNEX D2.1, where the possible solutions are explained.

4.6.1.1 Active systems

The active systems consist of those components that interface the vehicle with the infrastructure, including levitation, guidance, propulsion and suspensions system, which can be combined or decoupled (Figure 68).

Active system relies on electromagnetic suspension (EMS), similar to levitation technology found in several commercially operating Maglev trains today for both high and low speeds. However, there is a key difference from existing technologies. Typically, EMS uses only electromagnets for levitation, while the system used by Hyperloop (Hybrid EMS or H-EMS) adds permanent magnets to the EMS magnet (Figure 71 and 72). It requires a permanent magnet and electromagnet on the vehicle. The infrastructure has steel-made tracks. By attraction to the track, the vehicle levitates. However, without a control system, it is unstable. To stabilize the magnet's force, the electromagnet is controlled to weaken or strengthen the magnetic field, ensuring a constant air gap between vehicle and track.

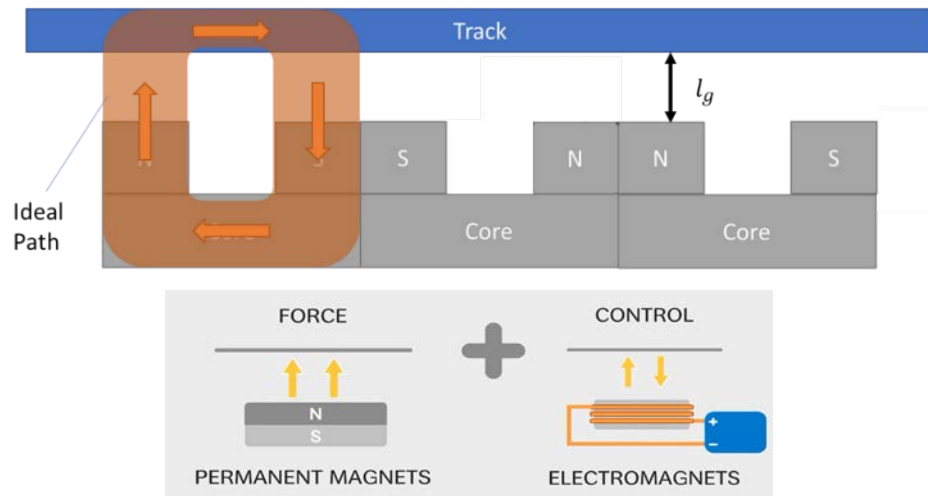


Figure 71. Top: Basic explanation of EMS. Bottom: Basic explanation of Hybrid EMS. Source: Universidad Polit cnica de Valencia

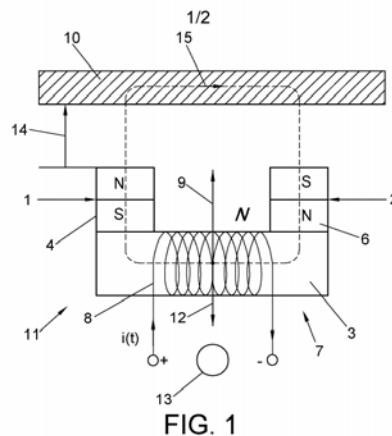


FIG. 1

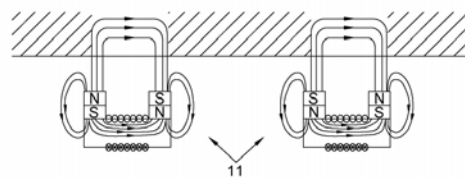


FIG. 2

Figure 72. Zeleros patent regarding EMS. Source: Zeleros

The electromagnet gets attracted towards the track. By actively controlling the strength of the magnetic flux, a constant air gap is maintained. The advantage of the H-EMS is that a large air gap between the track and magnet can be achieved by less energy compared to conventional EMS. HARDT levitation guidance and propulsion have been proven already in the propulsion levitation demo and at the low speed test facility (Figure 73). While Virgin Hyperloop One has performed a first successful passenger test at a 500 m test facility near Los Angeles, achieving a major milestone for the Hyperloop industry.

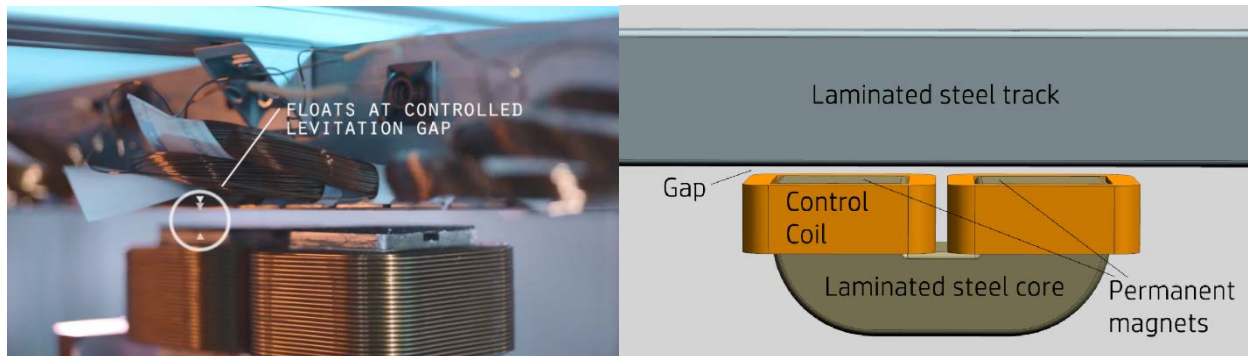


Figure 73. Sketch of EMS with permanent magnet in the centre of steel core and close to the magnets at HARDT's propulsion and levitation demo

4.6.1.2 Passive systems

Differently from the active systems, the passive system does not require any active control. They are based on the electromagnetic induction. This system uses vehicle-side permanent magnets or superconducting electromagnets and highly conductive guideway infrastructure that generate opposing magnetic fields through induction. Several vehicles in the Space X competition utilized this technology mainly due to its reliability and stability. The *first Delft Hyperloop pod*, but also the *MIT and WARR pod*, for the first competition utilized this concept due to its simplicity and reliability.

In addition, this system is not dependent on the energy usage. However, the disadvantage is its drag behaviour where the speed decreases after a peak has been reached. Utilizing the magnet properties this functionality can be further adjusted.

The EDS system has two main implementations:

1. MLX Shinkansen Maglev using superconductive electromagnets on vehicle and specific arrangements of 8-shape coils on track side. This system combines levitation and guidance with one of the best EDS performance, however at the expense of very high installation and maintenance cost on the track.
2. Implementation of EDS that utilizes the arrangement of magnets in Hallbach array fixed on the moving vehicle. The Hallbach array arrangement, illustrated below, enables to focus the high magnetic field energy towards the track, without the need of superconductors. It is a passive system that requires only motion of the vehicle and no power supply. Reaction plates can be installed on the bottom, for levitation, and on the side of the track, for guidance (Figure 74).

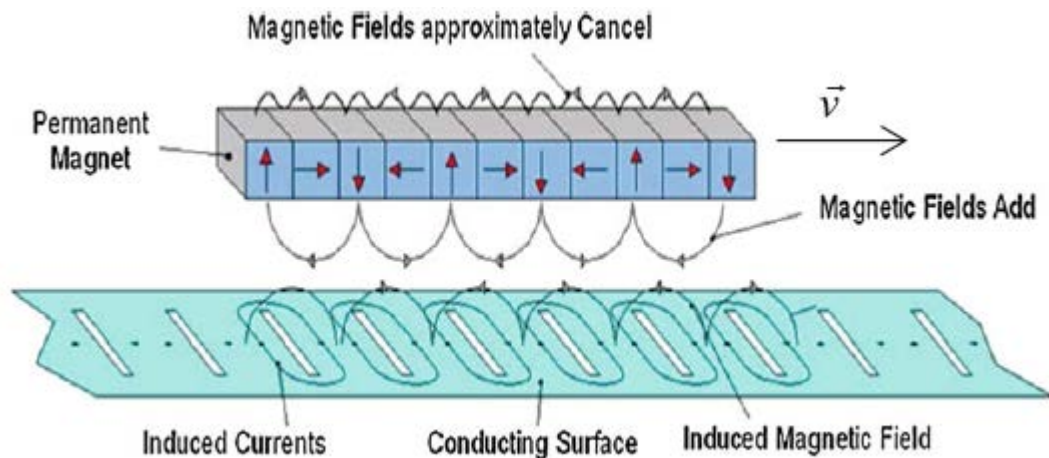


Figure 74 Illustration of Hallbach array inducing currents into a conducting plate.
Ref. Han, H. S., & Kim, D. S. (2016). Magnetic levitation. Netherlands: Springer.

The simplest form of the track is a simple aluminum plate. However, the disadvantage is that at high speed, induced currents are only generated in the top layer of the plate, called skin depth, resulting in high heat losses and magnetic drag. In order to avoid this issue, improved alternatives to reaction plate, called Inductrack™¹⁶ have been designed. The Inductrack consists of a set of transversal rungs, each rung being a stack of thin elements (interwined Litz wire or laminated aluminum sheets). This arrangement reduces heat losses and drag.

Hyperloop Transportation Technologies (HyperloopTT) is utilizing the Inductrack™ technology, combining landing gear at low speed with efficient levitation at high speed¹⁷. The advantage is seen in avoidance of control and power supply failure modes.

Differences, advantages and disadvantages between passive and active systems have been depicted in HYPERNEX D2.1.

4.7 Propulsion

4.7.1 Linear Synchronous Motor

In the implementation where the vehicle propulsion comes from a linear synchronous motor, the magnets on the vehicle serve as the rotor. The track serves as the stator, with the motor windings fitted in slots in the laminated metal track. Figure 75 depicts schematics of a magnet together with a slotted beam, fitted with stator windings through which current flows such that a net propulsive force is generated. All propulsion power therefore comes from the track, which means that no

¹⁶ Inductrack: [10.1109/77.828377](https://doi.org/10.1109/77.828377)

¹⁷ <https://www.hyperlooptt.com/technology/>

power equipment is carried on-board the vehicles. The propulsion system at the same time also functions as the nominal braking system, which is regenerative. The braking energy is temporarily stored in accumulators at the stations and used for the acceleration of the new vehicles.

Propulsion power is needed to accelerate the vehicle and to overcome air and magnetic drag. With the low power consumption during cruising, the vehicle only needs small amounts of power during the cruise speed segments. This enables the use of a low power motor over the coasting section of the tube and a high-power section only for acceleration and deceleration, which reduces the cost of the track.

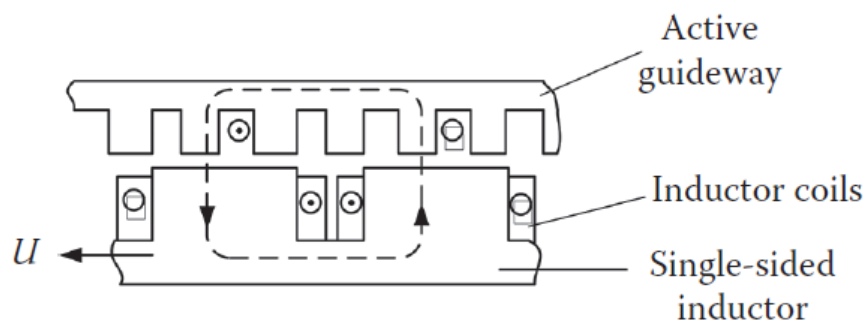


Figure 75. Schematic picture of linear motor. Source: (Boldea, 2013)

4.7.1.1 Linear Reluctance Motor

A linear reluctance motor (LRM) is an electromagnetic motor which produces magnetic forces to push the vehicle forward (Figure 76). In order to produce magnetic forces, some coils from the stator (S1, S2... in Figure 77) are powered up by direct current, producing a horizontal magnetic force, aligning in the vertical direction the teeth from the translator (T1, T2... in Figure 77) with the coils. At this point, these coils are switched off and the following coils are powered up, forcing the teeth to be aligned again with the following coils, and so on, producing a linear movement of the translator. For the vehicle to move forward, it must be mechanically attached to the translator.

However, together with the force produced in the horizontal direction, a secondary vertical force is generated. In order to avoid movement in the vertical direction, Hyperloop developers utilizing this motor will place enough stators to compensate the vertical force and allow to work with smaller coils since the number of coils is doubled.

The main advantage of this system is its high power to motor weight ratio onboard the vehicle, since the heaviest part (the stator) is installed in the tube. In order to reduce Hyperloop's infrastructure cost, once the cruise speed is reached, Hyperloop developers utilizing this motor switch the propulsion system to aerodynamic by means of an axial compressor (§2.15.4.1). In this way, the linear reluctance motor is only installed at the beginning and at the end of the tube, making the Hyperloop vehicle more scalable.

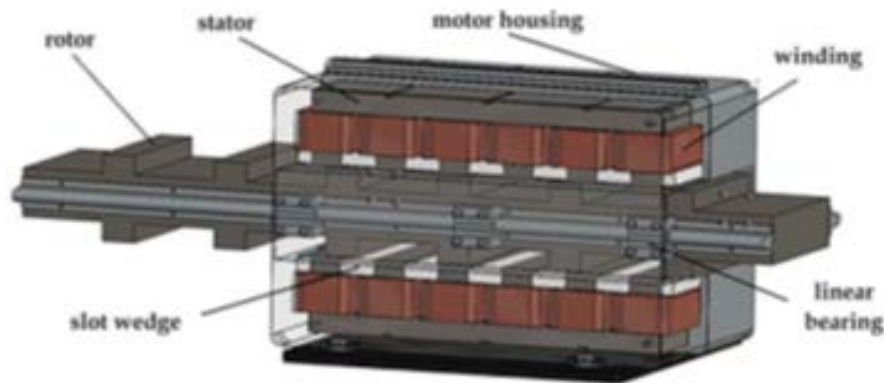


Figure 76. Representation of a LRM. Source: (Chen, Cao, Ma, Feng, 2018)

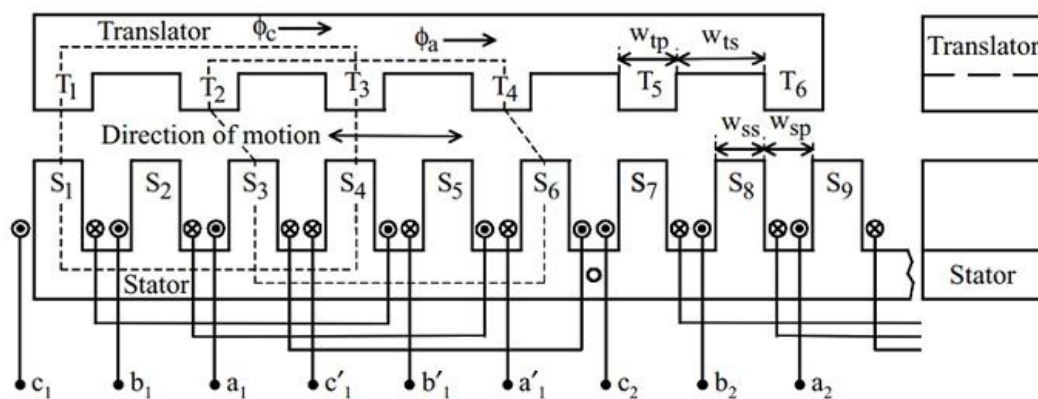


Figure 77. Schematic picture of a LRM. Source: (Krishnan, Sitapati, 2001)

4.7.2Turbofan propulsion system

Elon Musk's original *Hyperloop Alpha* called for the implementation of a vehicle-mounted turbofan as the vehicle's primary means of propulsion. This solution employs a front-mounted turbofan to overcome the *Kantrowitz* limit to actively transfer high pressure air from the vehicle's front to the rear (Musk, 2013) (Lluesma Rodríguez, González, Hoyas, 2021). By achieving higher blockage ratios, the tube diameter could potentially be reduced, lowering capital costs (Figures 78 and 78). Another advantage of this solution is that linear motors only have to be installed in the first kilometres of track for the initial acceleration, reducing the overall infrastructure costs. Conversely, the vehicle must have some onboard energy storage systems to provide energy for the cruising phase. This is the approach used by Zeleros and the Korean *HyperTube* train.

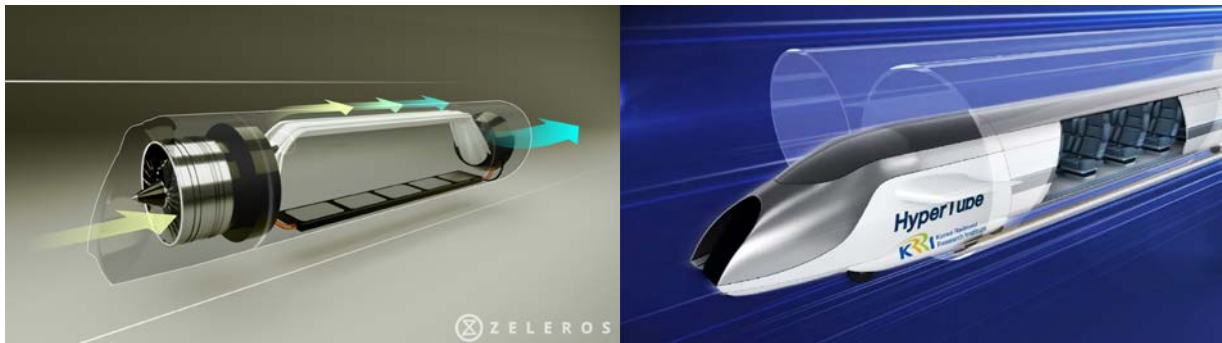


Figure 78. Turbofan propulsion solutions by Zeleros (left) and Korean HyperTube (right)

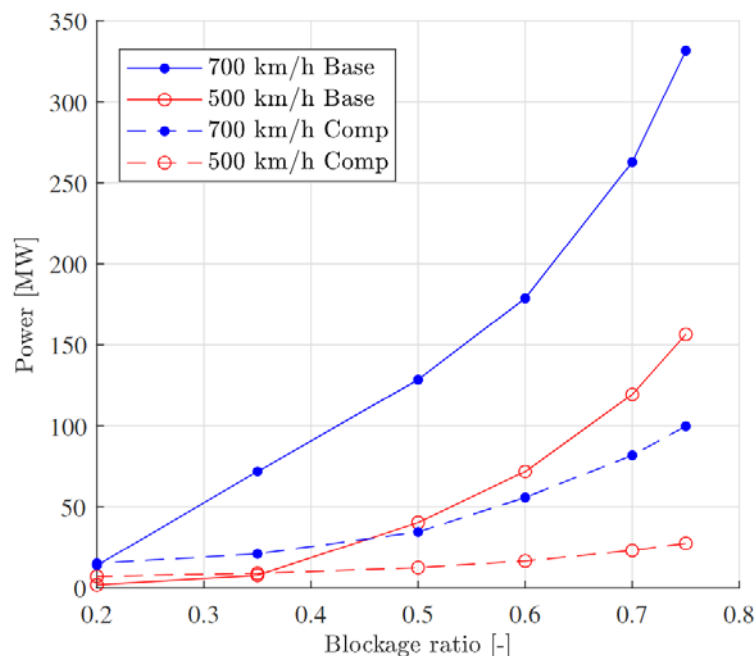


Figure 79. Required power comparison for different blockage ratios and speeds. With and without the compressor technology. Source: (Lluesma Rodríguez, González, Hoyas, 2021)

4.7.3 Suspension

In series systems with the levitation magnets, another layer of suspension works in parallel to filter the vibrations, guarantee comfort for passengers in the cabin and provide safety and stability during the operation. This secondary suspension system works similarly to the ones used in HST and commercial Maglev, as this technology achieves excellent performance and comfort levels. Among the benefits, adjustability plays a major role, making this kind of suspension adaptable to different ride conditions and loads in the cabin.

As shown in (Strawa, Malczyk, 2019), the implementation of the active element in a primary suspension system improves performance. However, the secondary suspension improves ride considerably. Further research is needed in modelling and control design of a system in order to gain understanding of dynamic performance of the vehicle under varying conditions.

4.7.4 Control System

The control system regulates the vehicle magnetic suspension using measurements of its environment. In order to obtain a stable path control, the control system should control levitation, guidance and propulsion, energy storage and transmission, air cabin, etc.

A centralized control system on the vehicle will control all at once. Levitation control will control the path and the gap size of the vehicle and its levitation magnets. Guidance magnets provide roll stability, keep the vehicle on the right track and enables to take a switch. Propulsion control will match the acceleration profile of the vehicle to the linear motor or a compressor, switches in the concerned tube sections and also braking system.

4.8 Communication systems

Communications technology for Hyperloop is essential for several key features of the system, such as safety, operation and maintenance. In this section the systems that require communication links to the different types of required communications depicted within the communication systems overview. The possible solutions for communications within Hyperloop systems are depicted as well. In addition an overview of the corresponding systems in railway and aviation are depicted as well.

4.8.1 Communication systems overview

There are a number of systems within the Hyperloop and its network of tubes that will require communication for internal system functionality as well as for their mutual interactions. Communication systems are needed to facilitate exchange of information and interaction between several parts of the system: the infrastructure and all its parts, on-board the vehicle as well as for the communications between vehicle and infrastructure.

For these interactions different communications systems need to be defined and implemented. Several types and levels of communications can be defined, depending on the interacting systems and subsystems and operation scenarios. Based on the functional description provided in Section 3.4, four types of communication links are necessary:

- On-board vehicle;
- Vehicle to operating control system;
- Operating control system to infrastructure;
- Vehicle to vehicle.

4.8.1.1 On-board vehicle communication

Vehicles have multiples on-board systems that need coordination and interaction, such as guidance, propulsion, levitation, emergency/safety, environmental control and power supervisory systems. They require communication links for drives, environmental control, power management, braking, etc. in order to facilitate their control and monitoring.

4.8.1.2 Vehicle to operating control system communication

Vehicle to operating control system communication is needed for control and scheduling along the tube. The vehicle could report its position, speed or maintenance conditions, while the operating control system will provide guidance to the vehicles based on its scheduling algorithms.

Fixed infrastructure could report capsule locations, speeds and directions. The capsule can receive a localized input from scanning passive indicators along the tube.

4.8.1.3 Operating control system to infrastructure communication

Different parts of the infrastructure, such as the vacuum pumps, electrical equipment, etc. require monitoring for operations and maintenance. In order to facilitate the exchange of the information between various systems a permanent and stable communication link is required.

4.8.1.4 Vehicle to vehicle communication

The advancements on the area of vehicle-to-vehicle communications have led to the introduction of the platooning concept in the transport sector. Platooning relies on wireless vehicle to vehicle communications. Due to the fact that the vehicle can talk to each other the Cooperative Adaptive Cruise Control (CACC) can be applied and vehicle can reduce dramatically their reciprocal distance in space and time. The benefits brought by platooning along roads and railways are mainly in the increase of capacity and the reduction of energy consumption.

Applying vehicle to vehicle communications in hyperloop will enable vehicle platooning in the tubes. When vehicles are virtually platooned, the individual vehicles remain in control of their own acceleration/speed/position. Robust and reliable vehicle to vehicle communications must enable vehicles to use the received data to control speed as well as limit propagation of disturbances. This is necessary to ensure a stable and safe operation, as well as high capacity. In the study of (Mendes Borges, Quaglietta, 2021) the conclusion is that utilization of virtual coupling for Hyperloop operation could address the targeted high capacity. Further research is necessary to determine the relation to safety as well as to comfort for the passengers.

4.8.2 Radio/wireless communications for Hyperloop

The necessity for robust and reliable communication systems is high. However, the applicability of the current radio/wireless communications systems in a Hyperloop environment is not proven (Delft Hyperloop, 2019). It is an area that requires more study and research in particular to understand the applicability of the existing technologies and those under development for Hyperloop's high speed and low-pressure environment.

Several alternative existing technologies have been looked at by a modest number of researchers. A combination of 5G NR and WiFi-6 systems is envisaged as the basis for the Hyperloop communication system (Figure 80). Nevertheless, the current performances of these systems are not sufficient for Hyperloop, but the enclosed hyperloop environment allows at using multiple bands from 2.5 to 66 GHz that should enable high throughput and, in combination with the edge-computing networks, should overcome the challenges imposed by the Hyperloop environment.

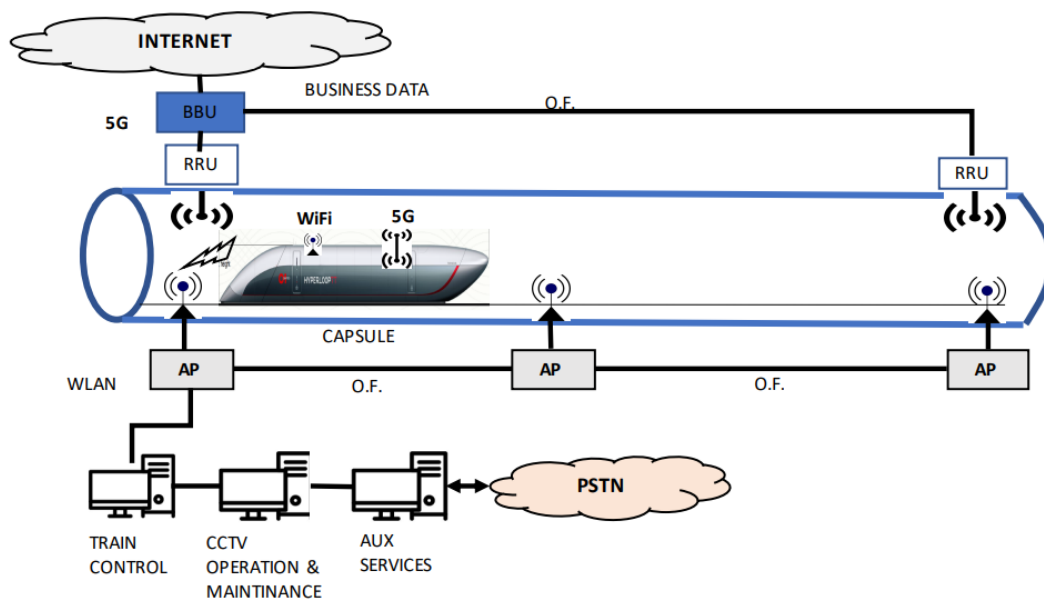


Figure 80. Communication network. Source: Tavsanaglou

(Delft Hyperloop, 2019) proposes a combined wired-wireless communication system utilizing the LiFi and Wi-Fi as wireless system and wired optical fibre to hyperloop base stations in a schematic network represented in Figure 81.

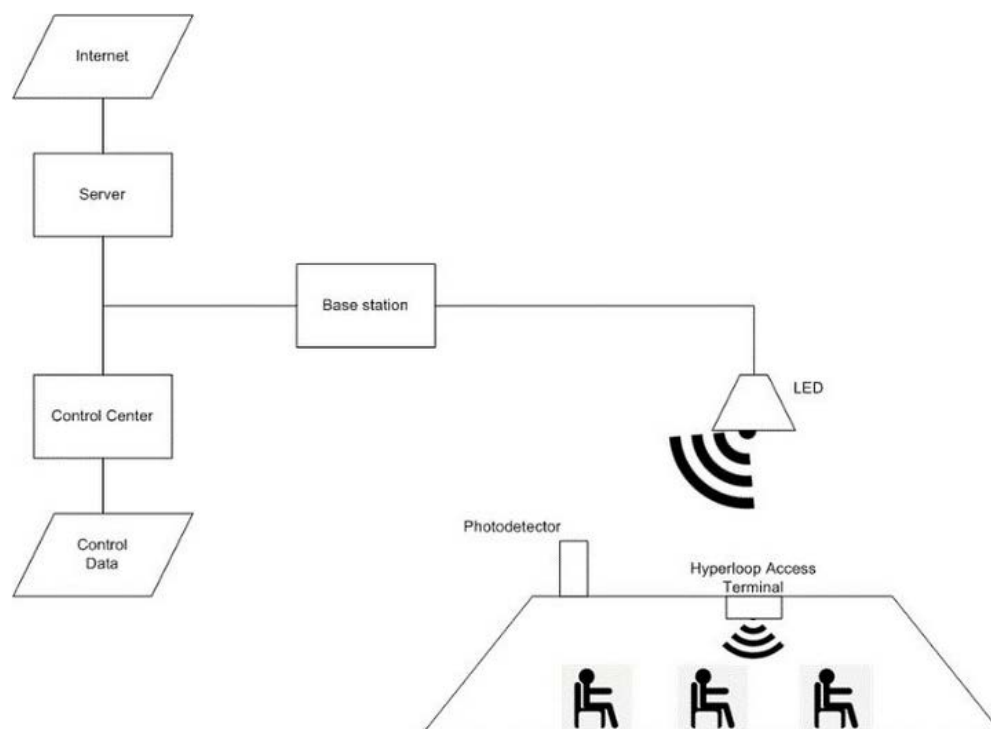


Figure 81. Schematic view of the Hyperloop communication system

4.8.3 Communication and signaling systems in railways

In the early years of railways, trains were kept apart by the use of the time interval system, but there was no means of knowing what might be happening once they were out of sight. If a train did not arrive at the next station when it was expected, a locomotive would be sent out to look for it. From the beginning of the 20th century, mechanical systems came into use to protect against the failure of drivers to stop at a signal at danger or if the permitted speed was exceeded. During the 20th century, mechanical technologies in railway signalling were replaced progressively by electricity, and later by micro-electronics. Additional and sophisticated functions were added over time, but the principles of railway signalling and interlocking remained unchanged from those established in the early years [Theeg, 2020].

Today, the European Rail Traffic Management System (ERTMS) has become a worldwide dominant solution for railway signalling and control systems, it has the potential to offer increased functionalities and become even more competitive. Nevertheless, current systems do not sufficiently take advantage of new technologies and practices, including use of satellite positioning technologies, high-speed, high-capacity data and voice communications systems (Wi-Fi, 4G/LTE, 5G), automation, as well as innovative real-time data collection, processing and communication systems. These have the potential to considerably enhance traffic management, including predictive and adaptive operational control of train movements, thereby delivering improved capacity, decreased traction energy consumption and carbon emissions, reduced operational costs, enhanced safety and security, and better customer information. In addition, ERTMS relies on GSM-R technology which is becoming obsolete with plans of telecom industry to end the support for GSM-R by 2030.

The work conducted within Shift2Rail Integrated Project 2 (IP2) Advanced Traffic Management and Control Systems focuses on innovative technologies, systems and applications in the fields of telecommunication, train separation, supervision, engineering, automation, security and improving digitalisation as one of the key aspects to enhance the overall performances of all railway market segments, starting from technologies and systems not yet largely applied to the railway field, such as satellite positioning and moving block. In this context, more than in others, a potential strong synergy with the development of the Hyperloop integrated communication platform is envisaged.

4.9 Energy consumptions

As explained in HYPERNEX D2.1 there are two main proposals for hyperloop infrastructures, which fully depend upon the propulsion system used.

For the on-track propulsion the main energy consumption of the infrastructure comes from the linear motors for the propulsion of the vehicle and the pumps to maintain the low-pressure environment. In aviation and railway, almost all energy use of the airplane and the rolling stock comes from their propulsion systems. In the case of the Hyperloop, this is the motor energy that is used to bring the Hyperloop to its cruise speed and overcome the magnetic and aerodynamic drag. For the on-board propulsion, the overall infrastructure energy consumption is significantly

lower compared to on track propulsion solutions. The on-board batteries feed the compressor. For both solutions, the pumps, by reducing the internal pressure, minimize the aerodynamic drag and therefore also the motor or compressor energy, but it requires energy. The lower the operating pressure, the higher the infrastructure energy consumption and costs necessary for the vacuum pumps. Therefore, operating at a higher pressure reduces infrastructure operating costs but increases the aerodynamic drag, increasing the energy consumption of the vehicle.

The energy consumption of the motor includes the energy for accelerating and decelerating the vehicle, to overcome the aerodynamic drag and the magnetic drag, all considering the efficiency of the motor. The relative importance of the acceleration/deceleration losses versus the drag losses depend on the length of the trip. For longer trips, the drag losses are relatively larger in comparison to the losses of acceleration/deceleration and vice versa. A constant drag force at cruise speed is assumed as a simplification. For the Amsterdam-Frankfurt study conducted by HARDT the energy consumption was determined as 38 Wh/passengers/km at a cruise speed of 700 km/h, (Table 18) (HARDT, 2020).

A comparative analysis of the various propulsion systems would be a recommendation for future research. Such analysis would be able to determine the efficiency of each of the solution under same conditions and (test) environment.

Table 18 Vehicle parameters for energy consumption based on the Amsterdam-Frankfurt route

Vehicle parameters	Value	Unit	Source
Cruise speed	700	km/h	HARDT
Frontal area	7.1	m ²	HARDT
Vehicle weight	23000	kg	HARDT
Seats	60	-	HARDT
Seat occupancy	60	%	HARDT
Aerodynamic drag coefficient	23	-	HARDT
Magnetic lift-over-drag coefficient	150	-	HARDT
Aerodynamic drag force	1.9	kN	Derived
Magnetic drag force	1.5	kN	Derived
Aerodynamic drag losses per km per passenger	15	Wh/ passengers /km	Derived
Magnetic drag losses per km per passenger	12	Wh/ passengers /km	Derived
Motor losses	11	Wh/ passengers /km	Derived
Total energy use per km per passenger	38	Wh/ passengers /km	Derived

4.10 Innovative Concepts

In this section innovative concepts for vehicle systems applicable to Hyperloop, railway and other guided transport modes are depicted. Only a selection of possible innovations is given.

Other examples to be looked at and relevant also for future research are depicted in the digital transformation of railways (Pieriegud, 2018):

- MaaS: towards intermodal mobility;
- PMaaS: digital services for rolling stock predictive maintenance;

- GoA4: automation and integration of train control systems;
- INTERNET OF TRAINS: creating value for multiple stakeholders.

4.10.1 Artificial Intelligence

Artificial intelligence (AI) is finding its way in many sectors and is gaining more and more momentum for application in various transport fields. Studies at (European Parliament Research Service, 2019) have shown the applicability of the artificial intelligence in road transport, railway as well as aviation. The applicability for Hyperloop has been studied by (Delft Hyperloop, 2019) and the potential of artificial intelligence for Hyperloop applications emerges in this two main areas:

- Designing and building a Hyperloop by designing the networks and stations capacity
- Automated operation and maintenance, where AI could be used as a tool for automated operation (timetables and scheduling), incident detection and safety/security mechanisms.

This is a new research area for all transport sectors and, as such also for Hyperloop, with the advantage of the possible application of these mechanisms already at the early design phase, particularly for non-safety critical applications. For safety critical functions the research pathways will be longer because a massive amount of data set would be needed to achieve SIL4 by using AI by making negligible the hazards of improper reactions to events uncovered in the AI training data.

4.10.2 Innovations in communication and signalling systems

The applicability of the existing communication systems as well as the ones currently under development is a research area on its own. These systems have not been designed with the requirements imposed by the Hyperloop low pressure and high speed environment system. Therefore, further research and testing is required to determine the most suitable technologies.

The following section describes the innovations planned by stakeholders in the field of communication and signalling systems in the railway (by Shift2Rail Joint Undertaking) and aviation (by SESAR Joint Undertaking) sectors. These provide a good set of references for the communication system in Hyperloop. In particular research areas are of interest.

4.10.2.1 Smart, fail-safe communications and positioning systems

This research in this area is divided in three topics:

- Development of a new communication system able to overcome the shortcomings in current ETCS and CBTC and deliver an adaptable train-to-ground communications system usable for train control applications in all market segments, using packet technologies (GPRS, EDGE, LTE, Satellite, Wi-Fi, 5G, etc.);
- Safe train positioning via the development of a fail-safe, multi-sensor train-positioning system, applying GNSS technology to the current ERTMS/ETCS core and introducing the use of other new technologies (e.g. inertial sensors, mobile network positioning) or of existing on-board sensors (e.g. accelerometers, odometer sensors). Usually in tunnels, the GNSS signal is lost and there is a lack of

other available information, which presents a challenge to these navigation systems; technologies like GNSS repeaters or beacons have achieved success in the trials made by Transport for New South Wales (NSW) in Australia or a mix of technologies have been proposed by Sun et al.

- Development of smart object controllers, consisting of autonomous, complete, intelligent, self-sufficient smart equipment able to connect by standardised interfaces with control centres, on-board units or other wayside objects and communicating devices in the area.

4.10.2.2 Traffic management evolution

The topics underlying this category, that could be relevant for a future Hyperloop traffic management system, are briefly introduced below:

- An optimised Traffic Management System through improved operations with automated processes for data integration and exchange with other rail business services;
- On-board Automatic Train Operation aiming to develop and validate a standard for all railway market segments (mainline/HS, regional, urban/suburban and freight);
- Research currently going on in the European project SORTEDMOBILITY about decentralised autonomous, self-organising scheduling decisions, taken autonomously by the trains by reciprocally negotiating with surrounding trains with a given local area.

4.10.2.3 Moving block, train integrity and virtual coupling

The topics focusing on enhancing the railway system overall capacity that could help Hyperloop to achieve high capacities safely are described below.

- Moving block aiming at improving line capacity by decoupling the signalling from the physical infrastructure and by removing the constraints imposed by trackside train detection, thereby allowing more trains on a given main line, especially for high-density passenger services;
- Safe train integrity aiming at specifying and prototyping an innovative on-board train integrity solution, capable of autonomous train tail localisation, wireless communication between the tail and the front cab, safe detection of train interruption and autonomous power supply functionality.
- Virtual coupling aiming at enabling virtually coupled trains to operate much closer each other and dynamically modify their own composition on the move, while ensuring at least the same level of safety as currently provided.

4.10.3 Aviation Communication Navigation and Surveillance

The Single European Sky ATM Research (SESAR) Joint Undertaking is leveraging the latest digital technologies to transform Europe's aviation infrastructure, making it safer, smarter and more sustainable. SESAR is the mechanism which coordinates and concentrates all EU research and development activities in Air Traffic Management (ATM), pooling together a wealth of experts.

SESAR European ATM Master Plan sets a series of deployment scenario for ATM solutions approaching maturity. Some of these could help improving the Hyperloop communication system, improving its safety, capacity and reliability. The roadmap defined by SESAR for the deployment of these technologies is represented in Figure 82.

4.11 Power electronics

Power electronics technology has gone through dynamic evolution in the last four decades. Recently, its applications are fast expanding in industrial, commercial, residential, transportation, utility, aerospace and military environments primarily due to reduction of cost, size, and improvement of performance (Bose, 2009). Power electronics can be found as well useful for several components of the Hyperloop system, such as linear motors, or some subsystems, such as converters. Some roadmaps made by institutions and researchers for power electronics gravimetric systems are gathered in Figure 83.

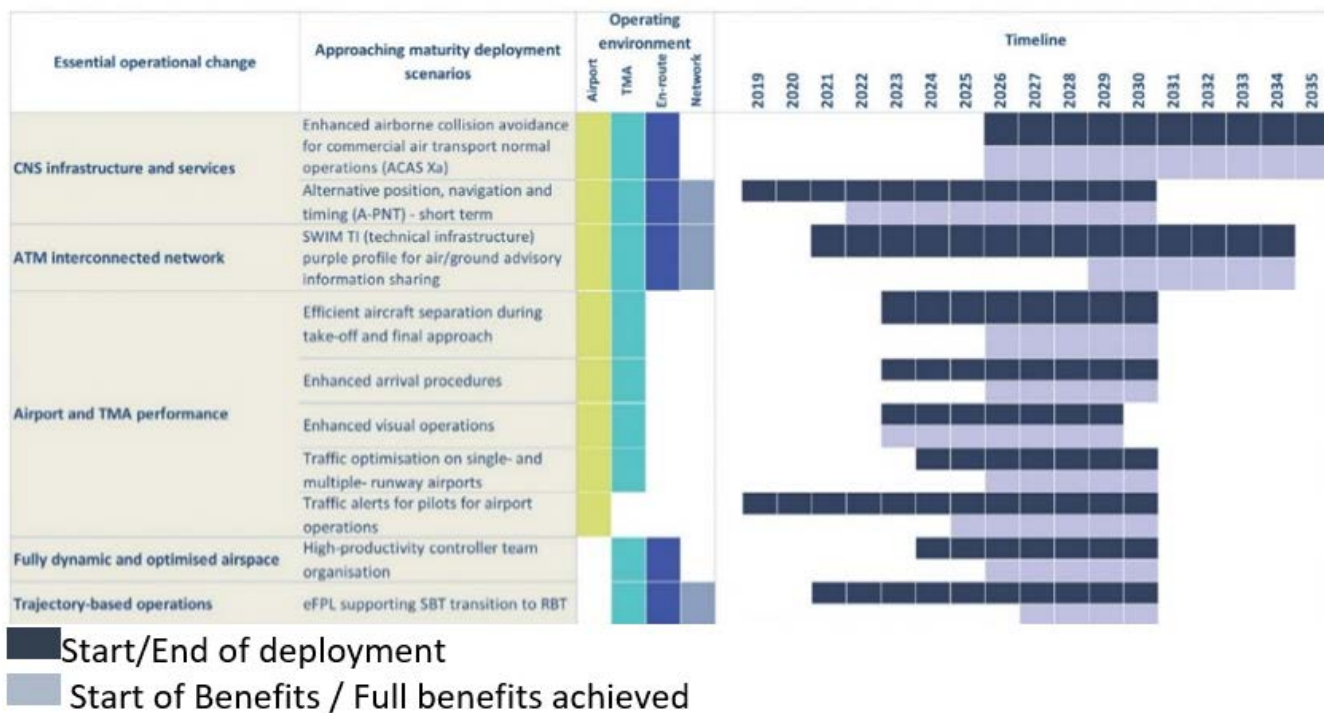


Figure 82. SESAR innovation roadmap for ATM innovations. Source: SESAR Joint Undertaking

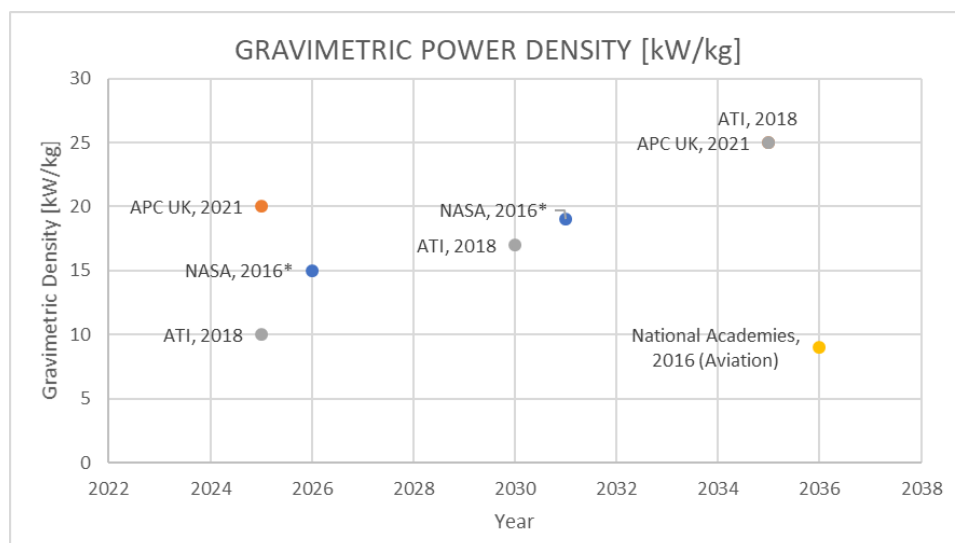


Figure 83. Power electronics gravimetric power density

One of the major challenges for increasing the gravimetric density of silicon converters is the thermal management. That is why during recent years, Silicon Carbide (SiC) power electronics became a potent alternative to state-of-the-art silicon (Si) technology in high-efficiency, high-frequency and high-temperature applications. The reasons for this are that SiC power electronics may have higher voltage ratings, lower voltage drops, higher maximum temperatures and higher thermal conductivities. It is now a fact that several manufacturers are capable of developing and processing high-quality transistors at cost that permit introduction of new products in application areas where the benefits of the SiC technology can provide significant system advantages. The additional cost for the SiC transistors in comparison with corresponding Si alternatives are significantly smaller today than the reduction in cost or increase in value brought from a systems perspective in many applications.

4.11.1 Motors

High power electric motors are necessary for compressor-powered hyperloop concepts. Today, electric motors can be found in many transport modes such as trains, car (Wakefield, 1998), ships or even airplanes. Therefore, its safety and reliability has been proved. The motors we can currently find have power ranges between two kW until hundreds of MW (GE Energy Power Conversion, 2016) (Figure 84). For Hyperloop, motors should be compact and lightweight. Figure 84 indicates some of the roadmaps set by companies or institutions for the gravimetric power density of motors.

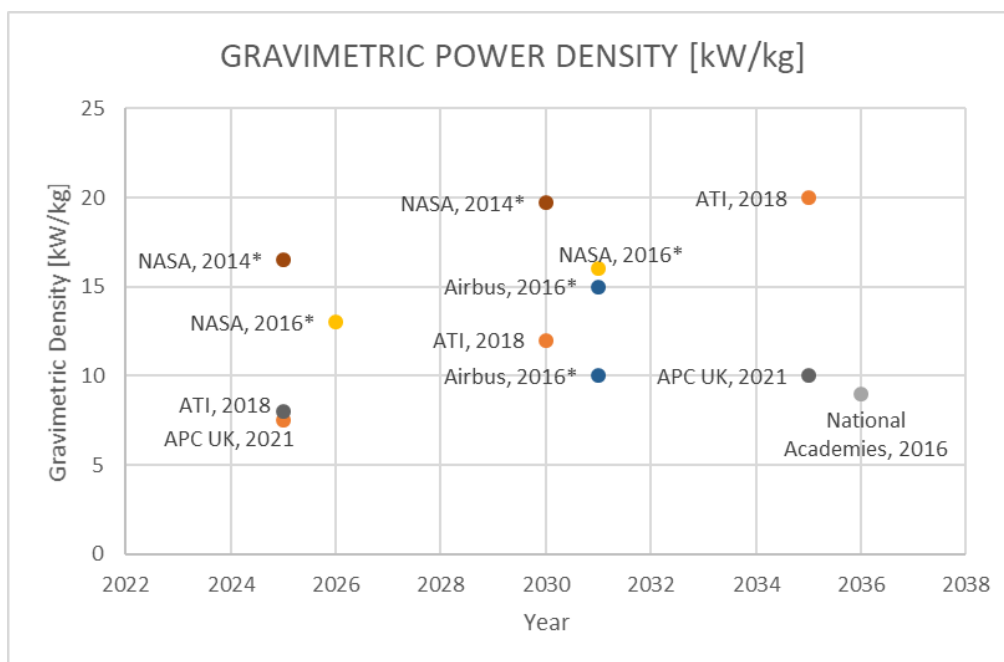


Figure 84. Electric motor gravimetric power density forecasts

There are some innovations also being performed in the field of motor materials. The rare earth magnetic material, Neodymium Iron Boron, forms the basis for the traction motors used in many

of today's leading electric vehicles. These magnets enable the design of motors, which offer extremely high torque densities, making them compact and lightweight, whilst also offering high efficiencies. However, some manufacturers such as Renault or Tesla have already employed other types of motors, wound rotor and induction motor technologies respectively, eliminating rare earth magnets. These and other technologies, notably switched reluctance motors and those replacing rare earth magnets with low-cost ferrites, can perhaps form the basis of even higher performance traction motors in the future (Widmer, Martin, Kimiabeigi, 2015).

Finally, researchers are trying to innovate as well in the field of motors by developing High-Temperature Superconducting Motors (HTS). Superconductivity offers zero (DC) to near zero (AC) resistance to electrical flow; thus, the use of superconducting materials can improve the overall electrical system efficiency while significantly reducing the size and weight of power components and machinery. Although superconductivity was first discovered in 1911, the requirement of an extreme cryogenic environment (near absolute zero temperature) limited its utility. With the discovery in 1986 of a new class of High-Temperature Superconductors (HTS) that operate at substantially higher temperatures (although still cryogenic), remarkable progress has been made in advancing a broader use for superconducting technology (Gubser, 2004).

Further investigations are being carried out to improve the superconductor performance for future designs sponsored by institutions such as the US Department of Energy to reduce the cost of the superconductor for future commercial applications of the HTS technology (Karmaker, Sarandria, Ho, Feng, Kulkarni, Rupertus (2015). The roadmap set by NASA for HTS motors is showed in Table 19.

Table 19. Technology Roadmap for Superconducting motors. Source: NASA

NASA technology roadmap for Superconducting motors	
By 2030	33 kW/kg
By 2035	41 kW/kg
Ultimate estimate	54 kW/kg

4.12 Conclusions on the technical components of the Hyperloop architecture

The technical components of the Hyperloop system as well as the innovative concepts currently under development in other transport sectors promising in view of Hyperloop future applications have been described. It can be concluded that the Hyperloop system is complex consisting of many sub-systems and components covering a wide range of science and technical areas. A multi-sector research is necessary to understand the interfaces, build and test prototypes and finally validate and select the most suitable technology to be utilized for commercialization. Several research topics are identified as integration and specification of the extensive list of short-term and long-term research presented in HYPERNEX D2.1. As next step, a European roadmap for Hyperloop



research and development needs to be defined. This would enable further developments and enhancements of this promising sustainable transport mode of the future.

5 Hyperloop Operation Concept

5.1 Introduction

Implementation of innovative technologies in transport field should forecast how users and systems related each other and with competitors, regarding application fields, such as:

- Operational procedures supporting different freight and passengers transport services;
- Testing methodologies and environmental impact;
- Intermodality and interoperability as a service (i.e. integration of Hyperloop in mobility as a service), city permeability by new generation stations concept, technical interoperability at component and system level (e.g. infrastructure, energy, traffic and risk management).

The section is organized following the *Concept of Operations* (ConOps) guidelines. A Concept of Operations is a user-oriented document that describes systems characteristics for a proposed from a user's perspective. A ConOps also describes user organization, mission and objectives from an integrated systems point of view and is used to communicate overall quantitative and qualitative system characteristics to stakeholders (IEEE, 1998).

This section aims at initiating the ConOps for future Hyperloop systems. These transportation systems include a low-pressure environment, where vehicles can travel at reduced air resistance, and can thereby achieve ultra-high speed. All the classical sections of a ConOps are not discussed here, while other sections, quoted in the scope, are mentioned whereas they do not figure in a typical ConOps. According with Wikipedidia “A CONOPS generally evolves from a concept and is a description of how a set of capabilities may be employed to achieve desired objectives or end state”.

The vision presented in this ConOps is an integrated approach for conducting passenger and cargo transport in a way that meets the needs of all stakeholders. It specifically discusses Hyperloop systems and therefore is independent of other transport modes, such as air, road or rail, except to the extent that the Hyperloop systems operate to ensure intermodality with those systems.

5.1.1 Intended audience

The intended audience for this ConOps document is twofold: stakeholders involved in designing Hyperloop systems and playing a role in their future operations and stakeholders affected by the hyperloop systems but not involved in shaping the experience. These groups include:

- HYPERNEX consortium;
- Designers and manufacturers of tube transportation systems, such as Hyperloop, which can include companies, researchers, employees and contractors;
- Partner organizations developing or constructing systems and components for the Hyperloop companies;
- Partner organizations operating Hyperloop lines/stations or various pieces of the Hyperloop physical and digital infrastructure or application developers;

- Transport regulatory bodies, such as the European Commission, U.S. Department of Transport, Transport Canada and associated or comparable entities;
- Environmental regulatory bodies, such as the European Environment Agency, US Environmental Protection Agency, Canadian Ministry of Environment and Climate Change, and associated or comparable entities;
- Customers of Hyperloop lines, such as freight carriers or human passengers;
- Suppliers of goods and services for the Hyperloop systems, such as local energy providers;
- Local agencies: cities, towns, villages, townships, airport authorities, etc.

Depending on the location of any Hyperloop line, the specific stakeholders may vary; however, they will generally fall into one of the aforementioned categories.

5.1.2 Methodology

This document has been prepared by several hyperloop developers and stakeholders. It is intended to be general enough to accommodate unique facets of any individual company's Hyperloop system design.

5.1.3 High-level system overview

Ultra-high-speed low pressure tube transportation is designed to allow near-supersonic intercity transport, connecting cities with a fixed guideway infrastructure. Tube transport is similar to rail transport but uses vehicles travelling inside a linear guideway rather than traditional railway cars travelling along a flat linear guideway. The vehicles can reach near-supersonic speeds thanks to the benefit of reduced air pressure inside the tube and the vehicles' levitation within the vehicle, which reduces friction at ultra-high speed. Hyperloop is a version of tube transportation.

Hyperloop systems generally include infrastructure and vehicles. A hyperloop vehicle, frequently appointed as vehicle, has fuselage and structure to transport passengers or cargo between cities. Hyperloop systems are typically designed to carry several vehicles travelling in the same direction simultaneously.

The vehicles may be computer-controlled and operated autonomously, enhancing passenger safety by eliminating human piloting errors. Hyperloop systems operate in a reduced-pressure enclosed environment, making air resistance much lower than in the outside environment. The enclosure for this environment can be constructed out of steel, concrete or composite materials. It can be built below ground, at ground level or above ground supported by pillars. In order to achieve maximum operating speeds, the infrastructure is designed to be as vertically and horizontally straight as possible, to avoid sharp curves. While passing from a straight to a curved infrastructure, the vehicle's speed must be reduced to avoid G-force sensations which would create an uncomfortable passenger riding experience. The smaller the radius of curvature is, the lower the vehicle's speed could be and the longer the travel time will be. According to maximum speed and some other factors to assess, the minimum radius of curvature that allows maximum reduced speed should be defined.

5.2 Operational concept

5.2.1 Assumptions and constraints

5.2.1.1 Assumptions

Exploring the future, key assumptions are done to set up a vision for integration of this new transportation system. Key assumptions listed below are grouped in different topics: a) *A new transport mode*; b) *Advanced technologies*; c) *Environmental framework*; d) *Standardization Development*.

a) A new transport mode

Hyperloop is dedicated to the transport of goods and/or passengers. This new mode needs to comply with environmental, economic and conditions of the 2nd half of this century. This challenge leads to research and development of new ways of thinking, technologies and human relationships to develop a mode which is fast, environment-friendly, reliable and safe.

b) Advanced technologies

Hyperloop systems will be based on several advanced technologies and do not require the development of new technologies according to Oxford definition *technology that radically alters the way something is produced or performed, especially by labour-saving automation or computerization; an instance of such technology*. However, any Hyperloop designer reserves the right to evolve the existing technology or even to create a new technology.

c) Environmental framework

To help combat the environmental crisis, hyperloop shall be designed to minimize its carbon footprint. For sustainability, there is an optional concept where the system is powered by local and renewable energy such as solar panels along the route or other local electricity providers.

The construction phase also has the potential to contribute significantly to the system's environmental impact. Therefore, it is preferable that construction methods also be chosen to minimize environmental impact.

d) Standards development

As this system is completely new, there is no reference for how it must be designed or function. Standardization administrations are expected to create standards with system developers to ensure applicable standards exist for Hyperloop. This work is already in progress in North America and Europe (CEN-CLC, 2021), where standardization agencies are building frameworks for a global standard.

5.2.1.2 Constraints

The following constraints exist around the development of Hyperloop systems:

- Several transport systems already exist, including travelling by air, road, rail, waterborne and others; therefore, some stakeholders may not see the need for a new mode of transportation;
- Some components needed for Hyperloop systems may not exist off-the-shelf, necessitating that hyperloop developers, partners or suppliers develop new products for specific needs;
- Most government organizations have not yet been involved in advancing Hyperloop development, it is not based only on funding but on involvement at all aspects, including political involvement, meaning that private companies have predominantly relied on private budgets to develop their systems;
- Hyperloop systems complexity necessitates that developers choose numerous knowledgeable partners to help create the technical solutions;
- Implementation of too-restrictive standardization decisions could constrain Hyperloop system developers from taking full advantage of their unique designs, as well as constraint future innovations.

5.2.2 Stakeholders

The following section describes stakeholders impacted by, or having an impact on, the Hyperloop systems (Figure 85). Moreover, the overall quantitative and qualitative system characteristics are communicated to the stakeholders. That means understanding the interests of each stakeholder in front of the system, and their expectations.

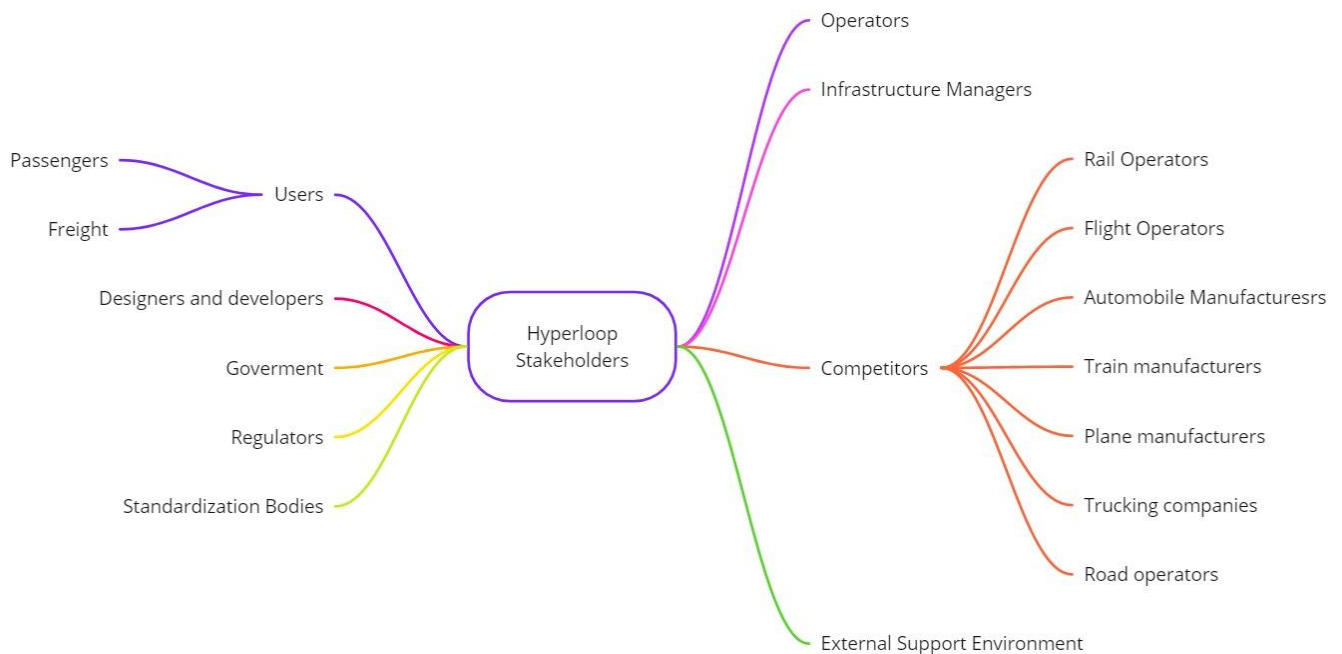


Figure 85. Hyperloop stakeholders

5.2.2.1 Users

Users refer to passengers and/or freight carriers.

Passengers are travellers who ride on the Hyperloop in order to get from origin to destination. Passengers could be further subdivided into categories, such as commuters, business travellers and leisure travellers. Generally speaking, passengers are interested in accessing a transportation system which is quick, timely, safe, comfortable and affordable. Different individuals will prioritize these criteria in different ways.

Freight carriers are organizations, which transport freight between locations and use a Hyperloop system as the mode of transport. Generally, freight carriers are interested in using a transport system, which is fast, reliable and affordable. Different carriers and different types of goods necessitate that these factors be prioritized differently. For example, carriers of time-sensitive goods will prioritize speed whereas carriers of non-urgent goods can prioritize price.

5.2.2.2 Operators

The operator is the organization which manages operations of a specific hyperloop line, including managing schedules, day-to-day operations at each station, vehicle maintenance, running the control and operations facilities and other general operations activities.

Operators of a Hyperloop system will vary depending on the location and the mandates of that respective line's private investors and local governments. One option will be for the Hyperloop developer and/or the infrastructure investors for a specific corridor to act as the operator of that specific line, managing operations in-house. Another option will be for the Hyperloop developer and the investors to find an external organization to manage operations. A third option will be for the governmental bodies to require that a specific group or organization be given the operator role. In either case, the operators must be involved in discussions with the relevant regions during the planning and construction phase for a new tube transport line.

In any option, operators generally desire for the tube transport system to be profitable and easy to operate.

5.2.2.3 Infrastructure Manager

The infrastructure manager is an entity responsible for the safe and secure management of traffic and infrastructure, which includes the following activities:

- Register and maps;
- Planning and publishing closures and restrictions;
- Infrastructure preparation before departure;
- Infrastructure maintenance, including stations, depots, etc.;
- Operations management, also in case of emergency;
- Supporting of station master's work;
- Organization of human resources management;
- Access fee calculation;
- Assistance to Persons with Reduced Mobility (PRM) in boarding/alighting operations;
- Data marketplace.

5.2.2.4 Designers and developers of the system

Each system designer of competing tube transportation systems impacts one another. These organizations collaborate in advancing the industry at large, but also compete for the right to construct their infrastructure in corridors around the world. The infrastructure and technology designs by each system designer have similarities but are not identical. Each of these entities is mostly interested in ensuring it designs a constructible, functional, efficient transportation system which can be commercialized around the world.

5.2.2.5 Competitors

Competitors of Hyperloop systems include:

- Rail operators, who offer competing services for medium-distance passenger or freight transport and already have constructed and operated infrastructure in several locations;
- Flight operators, who offer competing services for medium and long-distance passenger and freight transport and already have operations established between cities that have adequate airports;
- Automobile manufacturers, who depend upon travellers to choose driving rather than Hyperloop as their transport mode of choice;
- Train manufacturers, who sell a competing transport mode to operators that could be interested in instead operating a Hyperloop corridor;
- Plane manufacturers, who sell a competing transport mode to operators that could be interested in instead operating a Hyperloop corridor;
- Trucking companies, who offer competing services for short and medium-distance freight transportation, wherever adequate roadways are available;
- Road operators, particularly for toll roads, who depend upon travellers and freight carriers to choose driving rather than Hyperloop as their transport mode of choice.

Additionally, hyperloop developers may be viewed as competing with each other.

5.2.2.6 Governments

Governments and other authorities are responsible for planning and very often for funding of the transport infrastructure.

5.2.2.7 Regulators

Relevant regulatory bodies for Hyperloop vary in each region and country. The regulators that impact the system include the transport, environment and energy authorities, among potential others.

5.2.2.8 Standardization Bodies

According to the French Standardization body AFNOR, a voluntary standard is:

A frame of reference providing guidelines, technical or qualitative specifications for products, services or best practices to serve the general interest. It is the fruit of consensual co-production

between the professionals and users involved in its development. Any organization is free to refer to it or otherwise. This is why we call it voluntary ... However, in order to respond to specific situations of general interest (health field, need for security ...) the administration may decide to refer to a voluntary standard to ensure a certain level of protection for people and materials. The voluntary standard quoted in the regulation then becomes, in this very specific case, mandatory application.

Standardization bodies are organizations, which develop and coordinate the writing of technical standards. Key developers/organizations get together to jointly create a standard if they see a potential in developing standards that will give access to a much larger marketplace rather than a scattered landscape of different tech being used. Otherwise, they are quite unfavourable towards standards developments and applicability of the standard.

The European Railway for Agency could be a reference for standardisation processes, at least in terms of requirements, methods and processes.

5.2.2.9 External Support Environment

The support environment refers to external factors in the environment, which enable the smooth operations of a hyperloop line. Specific examples include:

- Local transit: to efficiently get passengers to and from Hyperloop passenger stations, a robust local transit network is required;
- Last-mile delivery: to efficiently get freight to and from Hyperloop cargo stations, a robust local first-mile and last-mile delivery network is required;
- Goods storage: some cargo sent along Hyperloop systems may require storage before reaching the end destination; therefore, warehousing space at each city along each corridor must be adequate;
- Energy: some Hyperloop systems rely upon energy provided at regular intervals along each line; therefore, a robust and consistent supply of electricity or other energy is required; the related network can be built in parallel with the Hyperloop system construction if it does not exist already.
- Communication network: acquiring and exchanging data, voice, and even video signals between different devices or participants within the Hyperloop system is a key challenge considering the low-pressure environment and the ultra-high speed.

Additional aspects of the support environment may be identified in the future.

5.2.3 Future operational environment

5.2.3.1 City permeability and new generation station concept

The society, in which a Hyperloop system will be operated will be different from today. Many potential drivers of changes have been identified:

- Growing population around the globe, especially single households, localised in Asia, Africa and Middle East: according to UNO, 68% of the population will live in cities by 2050;
- Aging population;

- Deep poverty almost eradicated, rise of the middle classes, yet continued rise of inequality;
- People prioritize *green* leadership to fight climate change;
- Climate change to cause mass migrations, then more instability;
- Energy consumption to increase by 30% between 2019 and 2040, with 50% renewable source as a consequence of the start of the energy revolution (International Atomic Energy Agency, 2020) (Hammond, 2019).
- Political instabilities put international construction projects at risk;
- Difficulties to maintain extensive supply chains;
- Higher volatility of commodities and raw material prices, also due to population growth and resource scarcity, on medium to long terms.

Additional lifestyle and business trends may include:

- Rise of the individual and decline of social cohesion and mass market;
- People may have A.I. companions assistants;
- People may be augmented from their clothes, contact lenses, jewels to DNA analysis;
- Additive manufacturing and internet of things' collected data allowing mass customisation.

New trends for the future of the working society may include:

- More fragmented, diverse and informal economy (gig economy);
- People tend to have a better balance between work (increasingly remote with less time and less travels) and leisure (potentially more time and travels if comfortable and neutral for climate change);
- Advance of the sharing and circular economy;
- Due to the digital disruption and the lack of paying jobs, machines may be generating the wealth that will fund our societies.

The mobility landscape will be very different and more varied than today due to the convergence of many new technologies, added to greener behaviours (Figure 86):

- Individual and mass transport becoming more autonomous;
- Combustion engines may be forbidden in some countries for personal vehicles, especially in cities (Carroll, 2021);
- New forms of mobility emerge: personal mobility devices, underground to air, intercontinental to last mile for people and cargo, all greener and mostly electric;
- Intelligent algorithms and IOT data allow operators to propose mass customized travel offers to a diverse and changing population improving revenue opportunities and passenger satisfaction;
- Intelligent algorithms allow operators to optimize traffic management;
- New forms of mobility and digital revolution will continue disrupting tourism industries: the new players come from the digital industry and private people;
- Digital disruption continues with the rise of the shared mobility: as a platform and as a service, resulting in fewer idle vehicles and disruption of the traditional *private vehicle ownership* schema;
- Cities will be sustainable and *smart*, increasingly using sensors and wireless networks.

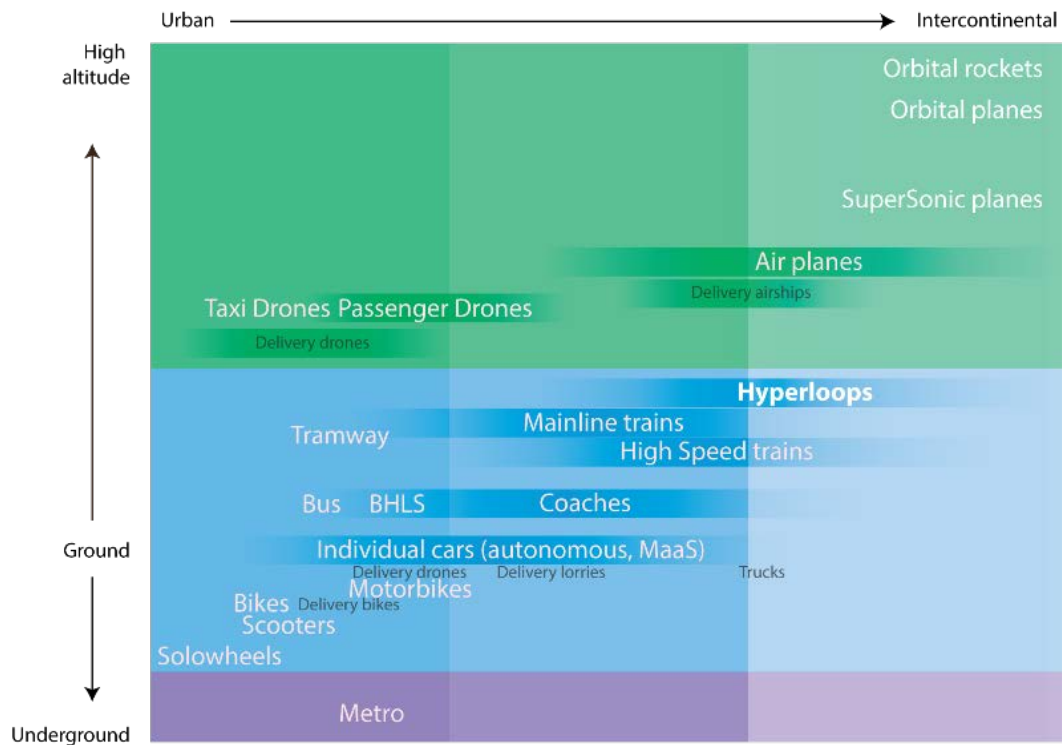


Figure 86: Potential transportation modes in the future

Hyperloop developers will use these future trends as inspiration in order to shape the Hyperloop system that is the most adapted to the future demands of its users, and their future environment.

5.2.3.2 Station model

Station model is detailed in HYPERNEX Deliverable 2.1.

The future paradigm previously described requires radical innovations to create a system that is competitive compared to the traditional transport modes.

By conceiving the infrastructure and the vehicle together, a Hyperloop system improves the passengers' experience and safety, makes the operations more flexible and allows new business opportunities for the operators. To enable passenger transport, a Hyperloop station shall have some characteristics that are common to traditional airport or train station and some that are specific. Hyperloop stations might propose the following characteristics, even though some of them might differ across different Hyperloop systems:

- Some designs can include areas for servicing the vehicles and buffering their availability;
- An area where the vehicles are boarded or disembarked;
- Stairs, escalators, lifts and ramps to ensure the accessibility to all passengers, especially for PRM or using personal mobility devices;
- Barriers or partition walls on the platform to prevent the passengers from crossing, falling onto, or entering the tube or guideway or structure where the vehicle travels;

- Monitoring system to ensure the passengers' safety;
- Smart security services to check the passengers before they access the platforms;
- Border control services to check the passengers in case of cross border trips;
- Intelligent design to ensure that arriving and departing passengers do not obstruct each other;
- Design allowing a high throughput of passengers;
- Optionally, an intermodal design to link with other freight and passenger transport modes in the region;
- Different arrangements according to operator's needs, local land constraints, funding needs or local demand;
- Amenities to insure the passengers' comfort, such as helpdesks, stores, washrooms, etc.

As for airports and train stations, a Hyperloop station can be sized based on the demand at that location. For example, passenger capacity can be set by adjusting the floor capacity, the number of vehicles docking stations or platforms and the departure frequency of the vehicles. Like at an airport, there may be differentiated service areas within a Hyperloop station. For instance, there may be certain high-frequency areas offering an economical travel option, premium areas or lounges for passengers seeking a premium offering, on-demand services or other options which could be added in the future.

To save space, vehicles offering different services can share the same docking station or platform, similarly to how passenger and cargo vehicles can share one tube infrastructure.

5.2.4 Description of Future Operations

5.2.4.1 Pre-Operational Planning

The first step in any commercial operation is the licensing and permitting application process. However, this does not occur until the research and development is completed, meaning that first, developing and testing at different scales for passenger and cargo operations must be successfully completed.

Small scale prototypes will help hyperloop developers refine technical solutions more quickly, debug troubles at lower costs and allow at showing solutions to the public at different locations. Each scale helps to develop a full-scale product and can be done in parallel to speed up the development process.

5.2.4.2 Testing Methodologies

Test and Evaluation involves evaluating a product from the component level, to stand-alone system, to integrated system.

Prototypes and/or Modelling & Simulation (M&S) used early in a program can help to predict system performance and identify new solutions to quickly reach expected goals. Both techniques can be used in designing, evaluating or debugging portions of a system before incurring problems.

The testing environment needs to cover the environment where the product will be used, without oversizing the testing environment conditions when it's not necessary to avoid exorbitant costs when tests fail. Operational tests have to be designed in order of complexity to increase reliability and robustness of the final product. All testing methodologies have to be flexible in order to integrate updates from feedback during the testing process.

A concept of operations is one of the initial stages in a system life cycle based on the V diagram, illustrated in Figure 87, widely used in a variety of Systems Engineering courses.

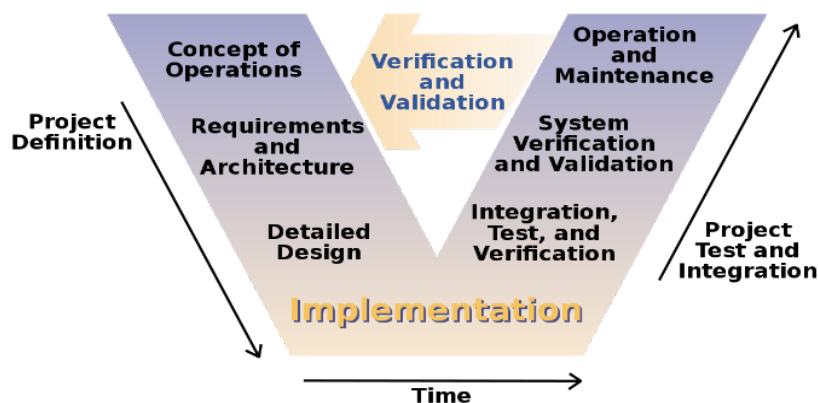


Figure 87: Systems Engineering Process

According to the V model, Hyperloop system testing will include *Installation Qualification (IQ)*, *Operational Qualification (OQ)* and *Performance Qualification (PQ)*.

Installation Qualification (IQ)

By performing IQ, manufacturers prove and document that equipment is in accordance with the requirements mentioned in the design qualification. This also includes checking the suitability of the working environment:

- Setting;
- Documentation;
- Environmental audit requirements;
- Security and safety checks.

Operational Qualification (OQ)

OQ relates to the proper functioning of machines in the chosen environment. The test assesses whether the equipment, including any customer-specific configurations, is performing to specification:

- Complete system check;
- Functional tests;
- Testing and modifying all variable parameters;
- Calibration.

Performance Qualification (PQ)

PQ verifies equipment related to the entire production process and as part of that process, to prove and document that they are performing reproducibly and consistently in accordance with their standard use within the specified performance parameters. Maintenance qualification relates to the operation, maintenance and servicing of the system, including service contracts:

- Personalized training;
- Application tests;
- System check for re-calibration and adjustment of the configurations;
- Ongoing maintenance;
- Service contracts.

5.2.4.3 Real-Time Operations

Once a hyperloop system is constructed, certified and ready to commence, the real-time operations can begin. For a typical ride starting from a Hyperloop station and arriving to another, the real time operations can be categorised in 3 parts which will be detailed after: a) *Departure disembarking/boarding sequences*; b) *Travel*; c) *Arrival disembarking/boarding sequences*.

The description below details the potential real-time operations for a typical Hyperloop line and stations, for a standard economy passenger trip.

a) Departure disembarking / boarding sequences:

- Arrival of the vehicle at the station;
- Vehicle stop at the platform;
- Opening of doors and/or platform gates, depending on the design;
- Passengers aboard can leave the vehicle;
- In some designs, the vehicle run to a service area where it can be cleaned up, maintained or at idle before a new departure;
- In some designs, the vehicle run to a service area where it can be temporarily stored for line capacity regulation or directed to another line;
- Once the vehicle is ready, new passengers will board the vehicle;
- Closing of doors and/or platform gates;
- If all systems are in order, departure of the vehicle from the station.

b) Travel

- In some designs, there are procedures for vehicle routing, pressure change or other handling after departure;
- Once inside the main corridor, the vehicle accelerates;
- Once the vehicle reaches the last part of the journey, deceleration begins;
- In some designs, there are procedures for vehicle routing, pressure change, or other handling before arrival.

c) Arrival disembarking / boarding process

Operations are similar to the departure disembarking/boarding sequences, previously described.

5.2.4.4 Operational procedures supporting different passengers and freight services

Hyperloop system flexibility allows multiple transport services according to operators' needs for passengers and freight services. Each developer has created, or will need to create, operational procedures for: a) *passengers' stations*; b) *freight depot*; c) *line management*; d) *vehicle maintenance depot*.

a) Passenger Stations:

- Welcoming passengers coming from the station entry or another transport mode;
- Welcoming passengers arriving from an hyperloop vehicle;
- Passengers' amenities;
- Border control if the line crosses a border;
- Security controls;
- Crowd management;
- Ticketing;
- Signalling and wayfinding;
-
- Passengers station maintenance;
- At some strategic stations: vehicle sidings or mini-depots to cover for eventual emergencies or to increase supply when needed;
- Some solutions may require a recharging area for the on-board power supply.

b) Freight depot:

- Management of the goods arriving in the freight depot from different transport modes (last mile delivery, trucks, trains, planes);
- Management of the goods arriving in the freight depot from an incoming vehicle;
- Transfer of the freight from a mode to another one;
- Storage management of the goods in transit;
- Border control, tariffs and customs taxes if the line crosses a border;
- Security controls;
- Staff management and safety;
- Light vehicle maintenance;
- Freight station maintenance.

c) Line Management:

- Traffic management system;
- Traffic distribution between different freight and passengers' operators;
- Airlock management;
- Line and airlock maintenance.

d) Vehicle Maintenance Depot:

- Light maintenance;
- Heavy maintenance;
- Cleaning;
- Refurbishment;
- Storage of the vehicles, including extra vehicles according to a spare ratio;
- Storage of the unused vehicles, including those with damage or other issues;
- Depending on the solution: vehicle recharging facilities.

5.2.5 Interoperability and intermodality of the hyperloop system

Interoperability is of the highest importance not only for the user experience, but also a necessity in achieving safe operations, seamless continental transport and integration with the other modes of transport. At this level of development, it is desirable to initiate further research with the focus on identifying various levels of interoperability and subsequently identifying the interoperability points and priority, safe operations being the highest priority. This thereafter links also to the integration with the other modalities, i.e. intermodality and inclusion of Hyperloop in MaaS services.

Putting in place the Interoperability for the hyperloop designers can have many advantages beyond homogenizing the Hyperloop system's architecture. Indeed, the interoperability of solutions in Hyperloop implementation in Europe can secure public and private investment. Additionally, global interoperability is a paramount condition for a safe, quality assured and efficient service but also a counter to a monopolistic situation or a fragmented market.

During the period starting in July 2020 and ending in March 2021, the European Commission DG-MOVE, Directorate-General for Mobility & Transport (DG-MOVE) commissioned a *Study on a regulatory framework for hyperloop, an innovative transport technology* to define the potential regulatory approach for establishing a dedicated legislation framework for Hyperloop. The report drafted the issues of interoperability and intermodality for a system, such as Hyperloop, and highlighted the hyperloop system's diversity by listing the differences of the system developers. The feedback from this report was that for the Hyperloop promoters, there is a desire to achieve interoperability from the start, both in physical structures and operating rules and at least to engage ad hoc activities on that particular issue from the outset of the European regulatory and standardisation developments. However, the Hyperloop developers felt that it is too early to achieve a harmonised system at this stage in the development as this would impact innovation and that safety and customer experience is the focus.

In the continuation and the extension of what has already been efficiently initiated by DG-MOVE in this study, the objective of this section is to initiate the definition of the interoperability for the tube transport systems considering each system's diversity but also the project's stage. The definition and challenges of the interoperability and intermodality will be introduced, then the possible categories and levels of interoperability will be presented, as of intermodality and finally the next steps to develop the interoperability and intermodality between the Hyperloop stakeholders will be suggested.

5.2.5.1 Interoperability introduction

As of today, there is no definition of the interoperability specific to the hyperloop system. The ISO definition is: Characteristic of providing an intended function in coordination with other components, the characteristic of sharing information with other system functions or components to provide additional functionality (ISO, 2006).

In (European Union, 2016) interoperability means the ability of a rail system to allow the safe and uninterrupted movement of trains which accomplish the required levels of performance.

The standards and regulation on interoperability can enable the appearance of competing products, only if they relate to the external behaviour, the functionality, or the interfaces of the system components to which the standards relate, rather than its internal design.

The right to exhaustive knowledge of the interfaces of a product is a right granted to the person who acquires it, thus conferring the possibility of making the product, both hardware or software, work with other existing or future products.

Interoperability has broad technical implications. It can also have an impact on the involved companies and organizations and poses essential questions. For example, these may relate to data and data exchange: do system designers or end users want to share their data? If so, to what extent and in what way? How must a standard be organized so that the targeted interoperability is both easily accessible and viable? How can we ensure that it is adapted to complex and sometimes contradictory needs? This is just one example of questions that interoperability may impose.

A wide range of proposed Hyperloop systems and operational concepts with significant differences are currently under development, which presents some key challenges in converging on a common vision of the hyperloop system.

5.2.5.2 Intermodality deployment

Beyond setting the interoperability's definition of the Hyperloop system, there is also a requirement to address intermodality between Hyperloop and other existing transport modes. As of today, there is no consensus on the definition of intermodality for Hyperloop systems.

For the transport of cargo, the definition of intermodal transportation is movement of goods (in one and the same loading unit vehicle) by successive modes of transport without handling of the goods themselves when changing (Commission of the European Communities, 1997). In other words, intermodal transport is a transport modality, which uses standardized cargo units, such as containers, swap bodies and semi-trailers that can be easily moved across different modes, such as ships, trucks or trains, to be brought to destination.

For the transport of passengers, intermodal passenger transport, also called mixed-mode commuting, involves using two or more transport modes in a journey.

To transport goods means to satisfy the need to move cargo from an origin point to a destination point, in the most efficient and effective way. Transport is effective when it responds to the requirements of the customer (i.e. in terms of speed, safety, flexibility), and is efficient when it

delivers the expected outcome minimizing the consumption of resources (money, fuel, labour, etc.). When performed well, the intermodal transport of cargo can allow economies of scale, cost control, safety and sustainability.

The challenges to ensure effective intermodal transport are:

- Relevance of volumes and distance: intermodal transport can be effective to transfer significant volumes on medium to long distance routes;
- Ability to organize logistics operations: intermodal transport requires an *industrial* approach to logistics operations;
- Capillarity of service: the effectiveness of intermodal solutions available in a certain region is highly correlated with the presence of intermodal terminals and freight villages, as well as the availability of rail services connecting the origin and destination points relevant for the customers;
- Transit time and speed;
- Nature and value of cargo: intermodal transport typically represents an attractive option for goods of middle value, which can be easily containerized and do not require special conditions, such as controlled temperature; high value cargo, small in size or lightweight, is usually shipped by plane, which is more expensive but faster; the Hyperloop system could potentially compete with planes on this market.

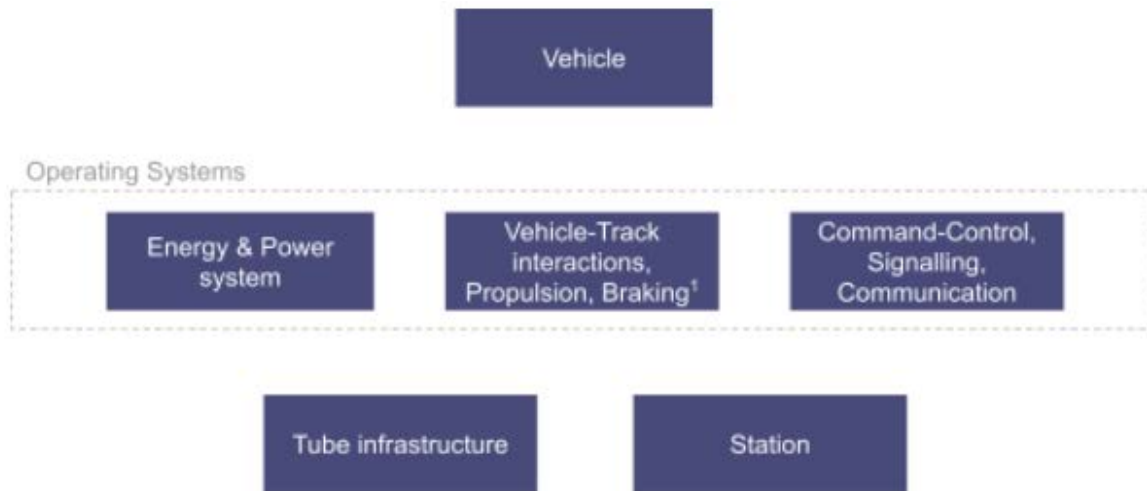
5.2.5.3 State of the Art

In the DG-MOVE report, the Hyperloop concepts proposed by the system developers were reviewed and a comparison table of the Hyperloop technologies was established. One fundamental question raised was to what extent interoperability would be required. Two options were explored:

- Is it necessary to aim at compatibility of different solutions delivered by different Hyperloop developers (vertical approach)?
- Would changing from one Hyperloop system to another be acceptable (horizontal approach), intra-Hyperloop mode? This assumes that free and fast passenger or cargo flow at Hyperloop stations, where the endpoints of hyperloop lines based on different technologies meet, is ensured.

A general Hyperloop system is composed of tube infrastructure, vehicles and stations, which, for all hyperloop developers are presently not developed as independent entities being able to interact with all types of components. The links between the vehicle and the tube infrastructure, between the vehicle and the station and between the tube infrastructure and the station are the *Operating Systems*. The core of the research and development of a Hyperloop system is to design these interactions. Three families of operating systems can be highlighted (Figure 88) within the reference architecture of the hyperloop system (CEN/CLC, 2021). The reference architecture, although initiated by Trasnpod, is a common work result of seven promoters of hyperloop in the EC, which has then been transferred into the ongoing JTC20 standardization activities.

- Energy & Power;
- Vehicle-Track interactions, Propulsion, Braking;
- Command-Control, Signalling, Communication.



¹ Vehicle-Track interactions, Propulsion, Braking. This refers to interactions based on the transmission of forces between the vehicle and track, such as propulsion, braking, stability and guidance, as well as on the mechanical configuration of the vehicle-track interface currently under development by hyperloop manufacturers in Europe

Figure 88: Reference architecture of the hyperloop system. Source: (CEN/CLC, 2021)

To ensure interoperability at the components and system level, all the above operating systems should be reviewed and shared within the Hyperloop community to ensure a common management.

5.2.5.4 Categories and levels of interoperability for tube transport systems

The interoperability of the hyperloop system can be defined considering two categories (Figure 89): *technical* and *business* interoperability (Westerheim, 2014).

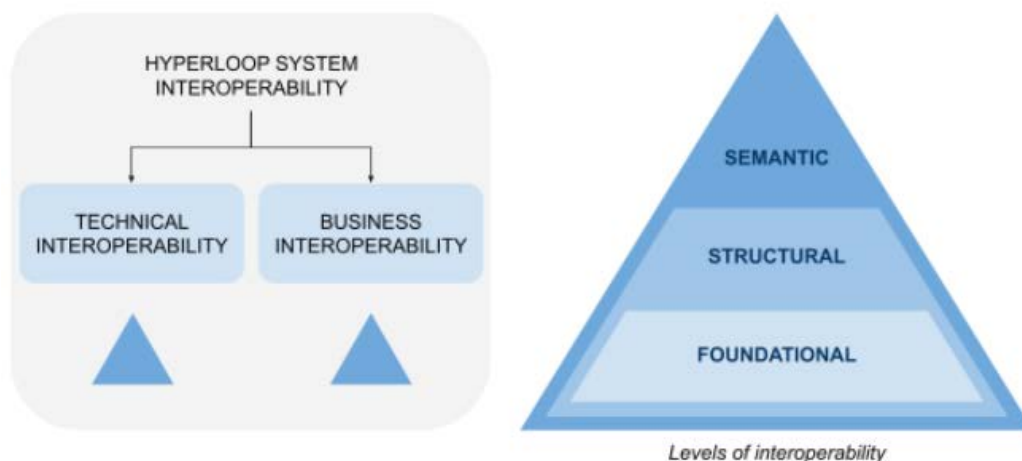


Figure 89: Categories of interoperability

These two categories of interoperability can be set at different levels: *foundational*, *structural* and *semantic* (Wolters Kluwer, 2014).

The *foundational interoperability* is the most basic one. It does not ensure an interoperability but intra-Hyperloop intermodality.

The *structural interoperability* is the mid one. It ensures the interoperability of the Hyperloop system but mostly only at the components level. A structural business interoperability ensures a fluent continuity of service for passengers and cargo.

The *semantic interoperability* is the highest level. It ensures the interoperability of the Hyperloop system level. A semantic business interoperability will ensure a fluent continuity of service for the passengers and cargo at the highest level.

The technical interoperability needs are based on the definition by IEEE:

The ability of two or more systems or components to exchange information and to use the information that has been exchanged.

There are two important issues in this definition:

- Systems or components are not interoperable if they are not able to exchange information, which requires a definition of standardised interfaces to be deployed in the involved systems or components;
- The information transferred between the different systems and components has to be in a context where the understanding of the information is clear so that the information can be used in the right way.

The business interoperability is also defined as:

The organizational and operational ability of an enterprise to cooperate with its business partners and to efficiently establish, conduct and develop IT-supported business relationships with the objective to create value.

In this sense, the business interoperability cannot be achieved and maintained in an efficient way, with a good quality, without the presence of technical interoperability. The set of interoperable and interconnected systems and solutions serves as an information infrastructure, where the physical and semantic communication of information is well working. To be able to achieve this situation there is a need to work both bottom-up and top-down. The bottom-up approach can secure the needed set of standards for communication and interconnectivity, linking the systems and solutions themselves. The top-down approach is needed to make it possible for the business to harmonise the functions and responsibility up-front of its business partners.

5.2.5.5 Foundational technical interoperability

To address intermodality between Hyperloop and other existing transport modes is a requirement. Without robust connections with other transport modes, tube transportation's proposed benefits will be diminished. Having foundational interoperability involves making the interchanges between transport modes as seamless as possible for passengers and cargo. Foundational

technical interoperability implies having connections between distinct Hyperloop systems on distinct platforms. The following technical requirements should be considered to help ensure intra-Hyperloop intermodality for passengers:

- Integrated hubs with other transport modes including bikes, buses, trains and planes, rather than having separate tube transportation terminals;
- Ensuring fast movement of vehicles in and out of terminals;
- Ensuring fast boarding and disembarking procedures;
- Determining the destinations of services within the intra-hyperloop station.

Intermodality/intra-modality of freight involves cargo transportation using multiple modes of transportation with minimum handling of the goods when changing modes, improved security, reduction of damage and loss and faster transport. The following technical requirements could be implemented for maximising the intra-Hyperloop intermodality of freight services:

- Alignment of Hyperloop systems with conventional container/pallet sizes;
- Quick loading/unloading principles aligned to existing connections with other freight modes.

Another essential consideration is data sharing between hyperloop transports. The willingness of business parties and organizations to expose their data usually comes with a strong desire to keep the ownership and full control of their data. The owners shall fully control the access rights to their data, the owner of data can control who can access the published assets (UITP, 2021). The ability of one IT system is to send data to another IT system. The receiving IT system does not necessarily need to be able to interpret the exchanged data, but simply be able to acknowledge its receipt.

5.2.5.6 Structural technical interoperability

The structural technical interoperability is the ability for some subsystems of an hyperloop developer to interact with the equivalent subsystems of another developer. What could be achieved in terms of structural interoperability, are agreements on specific elements, e.g. docking technologies and passenger access requirements. Indeed, for passengers' service, also minor differences in platform height and width clearance standards may cause lack of interoperability. Therefore, the specific elements/subsystems which could or should be considered as interoperable are to discuss.

In addition to designing interoperable subsystems, using modularity can be considered to prevent monopolistic situations. Nonetheless, developing the Hyperloop system architecture as a modular set of self-contained components would require utilization of the same system engineering techniques and a commonly agreed architecture.

In this context, automation plays a pivotal role to increase interoperability. It breaks complex processes into intermediate steps and provides their formal description to be processed by machine without any human intervention. In this direction, the systems architecture should promptly foster automation, which can be supported by automatic software building and automatic or semi-automatic deployment via scripts (UITP, 2021).

It can be considered to have connectivity between stations of different Hyperloop developers as represented in Figure 90. Structural interoperability should enable building, extension and scalability of tube transportation stations.

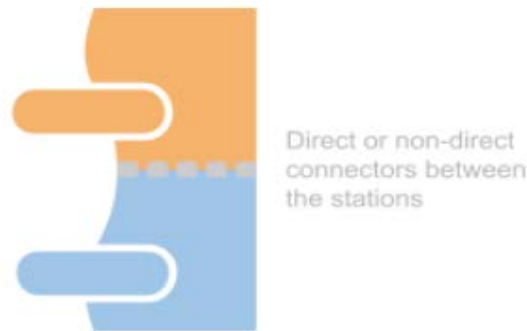


Figure 90: Representation of the possible connection between specific stations

Regarding the data sharing, ensuring a structural technical interoperability would engage the stakeholders to interactively cooperate in order to use each other's data and services as seamlessly as possible. Then, a uniform movement of data from one system to another would be ensured so that the operational purpose and meaning of the data is preserved and unaltered. To achieve structural interoperability, the recipient system should be able to interpret information at the data field level.

5.2.5.7 Semantic technical interoperability

Semantic interoperability for the Hyperloop system is the ability for the components of different Hyperloop developers to exchange/interact with each other. In practice, it means that the interoperable vehicle will be able to navigate the interoperable tube infrastructure without having to stop at the borders in order to exchange vehicles or drivers and without taking any activities by drivers. This is the highest level of interoperability which can be developed.

This semantic level of technical interoperability leads to an interoperable tube infrastructure to ensure the travel of any interoperable Hyperloop vehicle and an interoperable vehicle able to travel within any interoperable Hyperloop tube infrastructure (Figure 91).

In the same situation, an interoperable station will be able to host any interoperable hyperloop vehicle and an interoperable vehicle shall be able to board/disembark/get maintenance within any interoperable Hyperloop station (Figure 92).

Finally, an interoperable tube infrastructure shall be able to connect with any other interoperable tube infrastructure (Figure 93).



Figure 91: Representation of compatibility and non-compatibility of the tube infrastructure with all vehicles



Figure 92: Representation of compatibility and non-compatibility of the station with all vehicles



Figure 93: Representation of the tube infrastructure's non-connectivity

In practice, this semantic technical interoperability would involve ensuring convergence at least on the coupling between vehicles, braking, signalling, communications and operating rules.

5.2.5.8 Foundational business interoperability

The objective is to make the interchange between transport modes as seamless as possible for passengers. The following technical requirements should be considered to help ensure intra-Hyperloop intermodality for passengers:

- Integrated hubs with other transport modes including bikes, buses, trains and planes, rather than having separate tube transportation terminals;
- Ensuring fast movement of vehicles in and out of terminals;
- Ensuring fast boarding and disembarking procedures;
- Management of passenger and luggage flow;
- Integration of security screening (if necessary);
- Integration of ticketing.

Intermodality/intra-modality of freight involves cargo transportation using multiple modes of transportation with minimum handling of the freight itself when changing modes, improved security, reduction of damage and loss, and faster transport. The following technical requirements

could be implemented for maximising the intermodality-intra-hyperloop mode of tube transportation freight services across Europe:

- Alignment of hyperloop systems with conventional container/pallet sizes;
- Quick loading/unloading principles aligned to existing connections with other freight modes;
- Alignment of administrative elements and production of accompanying electronic documents-reservations, payments and invoicing, etc.

Another essential consideration is data sharing between hyperloop transports. The concept has been already discussed for the technical interoperability and is not changed right now.

5.2.5.9 Structural and semantic business interoperability

The structural and semantic business interoperability is the ability to ensure a fluent continuity of service for the passengers and cargo. It streamlines the customer journey and allows the user to experience a *seamless* journey that happens where network limits do not pose barriers.

The boundaries between the structural and semantic interoperability is not established here. What follows are systems or operations, which should be designed to reply to the interoperability needs. For these systems or operations, different levels of interoperability's application can be set. The aim is to define, for each system and operation, the level of application that the structural and the semantic interoperability request.

Structural and semantic business interoperability can involve the following systems and operations:

- Information system;
- Ticketing systems;
- Operation.

Ensuring interoperability of traveller *information systems* is about homogenizing the interface website-customer. It involves facilitating registering to and joining the ecosystem by providing a single-sign-on solution. This also makes it simpler for various transportation-related organizations and operators to enable their users to use the Hyperloop transport easily and seamlessly.

In line with these considerations, the current Asset Manager is integrated with an Identity Provider to provide maximum interoperability with other systems such as the Operator Portal. Hence, users can register to either the Asset Manager or the Operator Portal and have access to both systems.

The interoperability of ticket systems support involves using the same transport card, the user can travel on various networks, though each network retains control of the loading of its fare products on the common support.

The *ticketing systems* interoperability can be set at different levels: it can be used the combined pricing across network, recognized and accepted by the networks themselves. The juxtaposed pricing is also a possibility: acceptance on more than one transport contract. Finally, the integrated pricing corresponds to a single transport contract allowing travel on networks A and B.

The service interoperability is allowing the customer to travel on networks A and B with the same medium by having purchased both titles from the same network in a *cross-selling* scheme.

Structural and semantic business interoperability can also concern some phases of the operation of tube transport system's life cycle as the commissioning, the actual operation, the maintenance, as well as professional the qualification of the personnel who contribute to its operation. Some examples would be to homogenize the passenger's boarding and landing and the cargo's loading and unloading, being compatible with the standard cargo.

5.2.5.10 Synchromodality

Another option to consider is the possible application to Hyperloop of the synchromodality concept: the possibility of being integrated with other transport modes so that in case of a disruption passengers or goods can be automatically directed to alternative Hyperloop links and vice versa, as proposed by (Pfoser, Berger, Hauger, Berkowitsch, Schodl, Eitler, Markvica, Hu, Zajicek, Prandtstetter, 2018).

5.2.5.11 Next steps

The main finding of the evaluation is that there is no single interoperability problem amenable to a single interoperability solution, but that a common collection of specialized tools providing specific capabilities must be made available to stakeholders in order to compose different interoperability solutions for the particular interoperability problems arising from specific operational environments.

The common collection of tools must be developed according to an architecture that leverages standard languages and frameworks that separates application logic of business interoperability from the mechanics of the *pure* technical interoperability, delegate safety and reliability provisions to the underlying runtime environment and permit deployment in multiple instances of multiple runtime environments.

Interoperability will be achieved by standardizing the individual components, the sets of components and operations of the Hyperloop system. Only when interfaces are standardised, the different subsystems can inter-work to carry out a particular function. Standards must include test procedures so that equipment can be certified by the operators for interoperable use. The Hyperloop community shall work collaboratively to detail the interoperability goals through the standardization and regulatory framework and to integrate the established requirement and obligation. However, the focus of the definition of standards should be based on safety and customer experience without impacting innovation.

Considering the project's stage and due to the high variety of operating systems that are being proposed by the developers, it is very likely that the market will be the main driver that will decide how the hyperloop system shall be interoperable. Then when the first test track will be prepared, it will be possible to set the definition of interoperability. In order to define the levels of interoperability and its key points from today, there is a need for a test track that will allow at testing, research and analysis. The knowledge gathered will be utilized to define the key points and

the levels of interoperability, as well as to identify the requirements of system, sub-systems and various components.

Many studies or experiences demonstrate the interest to develop a common test track between stakeholders to enhance the interoperability.

A recent Orange Flag Evaluation (OFE) with the US Army and Air Force is the latest successful Lockheed Martin F-35 integration exercise to help make interoperability across the battlespace a reality in the near future. The exercise near Edwards Air Force Base, California, demonstrated the ability to integrate F-35 Intelligence, Surveillance and Reconnaissance (ISR) track data with the US Army's air and missile defence Integrated Battle Command System (IBCS).

Study to investigate the economic impact of Open Source Software and Hardware on the EU economy (Fraunhofer ISI, Open Forum Europe, 2021) identified strengths, weaknesses, opportunities and challenges of open source in relevant ICT policies, such as cybersecurity, artificial intelligence (AI), digitising European industry, connected car, high performance computing, big data, distributed ledger technologies and more. As shown in the report the total investments of 1 billion EUR from various parties in OSS resulted in 65-95 billion EUR gains for the European economy.

More specifically, in the transport sector, for 3 decades, the European target is to reach full interoperability in always over the TEN-T network and huge investments have been allocated to this aim in order to create a single European railway area.

The same should apply also to Hyperloop. If interoperability is to be pursued by developers of tube transportation, HYPERNEX has forecasted that it could potentially require more than 1 billion EUR in government funding. This estimation is based on the necessary costs that would be incurred for all system developers to significantly change their technology designs to make them compatible for interoperability, such as developing new infrastructure designs, power systems, levitation systems and engines. In addition, the funding would be used for further research as well as test tracks developments to validate and select the best performing concepts.

5.3 Risk Management

Risk management and safety are key aspects of a hyperloop system. The objective of the risk management process is to ensure that risks associated with the operations of the system are pre-emptively mitigated through intentional design; then, any remaining risks are methodically identified, quantified and mitigated to acceptable levels, as carefully analysed in Section 2.

5.4 Post-Operations Review

After the construction of a Hyperloop line has been completed and operations have commenced, a post-operations review should be conducted. The purpose of this review is to analyse the outcomes of the project and provide lessons learned for future projects.

Throughout the post-operations review, each Hyperloop operator or developer can conduct the following activities:

- Assess whether the project achieved its stated objectives;
- Assess whether any ongoing actions will be required in order to ensure that the project continues to achieve its stated objectives;
- Assess whether the financial and socio-economic benefits of the project have been realized as outlined in the business case;
- Evaluate whether the assumptions adopted in the business case were appropriate and accurate;
- Determine which outcomes, if any, could have been achieved in a more efficient manner;
- Determine what further actions, if any, should be taken in the future in order to minimize risks and better plan future projects.

After the post-operations review has been completed, the findings should be shared with the relevant stakeholders to ensure that current and future hyperloop projects make use of any new lessons learned.

5.5 Decommissioning

The decommissioning process refers to the act of making the system inoperable. Decommissioning may become necessary in the event that a line becomes unprofitable, if the purpose for which the line was built becomes obsolete or due to other unforeseen circumstances.

Prior to decommissioning any Hyperloop line, best efforts should be made to transfer the ownership of the line to another owner, if the main problem leading to the decommissioning, is profitability. Relevant authorities should be notified, as required by local laws, of the impending decommissioning process and the developer should publicly advertise the availability of the line.

If no parties emerge who are interested in acquiring the line, the decommissioning process will move forward. This will be included:

- Dismantling the system;
- Removing any harmful substances, toxins or materials (e.g. in historical infrastructure it was the case of asbestos, no longer used in new systems) if necessary;
- Transporting the dismantled system to its final destination, either a recovery or a disposal site;
- Recovering whatever materials can be recovered, to be sold for another use, or recycled;
- Disposing of whatever materials cannot be recovered.

The ultimate goal of the decommissioning process is to minimize the impact on the surrounding environment, and to recover whatever materials can be recovered for future use. To that end, it may be determined in some cases that the optimal decommissioning process will be to leave the infrastructure in place, rather than to remove it and risk disturbing the environment in the process. The decommissioning process for each line will be decided case-by-case based on a detailed assessment of the Hyperloop line in question, rather than having a uniform process to be applied indiscriminately.

5.6 Impacts

Until Hyperloop systems have been built and are operational, the real impacts are unknown. However, we can attempt to predict what impact the system will have.

5.6.1 Environmental impacts

Environmental impacts refer to the effect that the Hyperloop system will have on its surrounding natural environment, including air, land, water systems, animals, etc. Hyperloop systems are anticipated to impact their surrounding environment, however, due to the incipient nature of the technology, most of these impacts are still uncertain and cannot be properly quantified. Potential impacts include:

- Noise given the high operational speeds, particularly whenever a vehicle passes by any given location; this could be reduced by selecting noise absorbing materials for the construction of the tube or by increasing the tube thickness in specific sections of the lane (i.e. near populated areas) or finding quieter solutions for the system's operations;
- Land occupied or disturbed to build the support pillars, at-grade tubes or tunnels. During the construction phase, additional land may be disturbed by construction machinery and access roads; also visual impacts need to be account.
- Energy consumption, though being at zero direct emissions and ensuring traceability of the energy coming from renewable sources; however, there might be situations where this cannot be granted, resulting in additional greenhouse gas emissions, depending on the used source;
- Interruption of animal migration patterns, depending on the region.

Additional environmental impacts which are not yet foreseen may also become apparent after operations have begun.

5.6.2 Socio-economic impacts

Socio-economic impacts refer to the non-environment-related impacts that will occur during operations. Some operational impacts are expected to occur, including:

- Passengers may choose to travel more frequently as a result of the new faster travel option;
- The use of complementary transport modes, such as car, bus, train, plane may decrease in proportion with the increased use of hyperloop systems;
- Freight operators will be able to achieve faster delivery times and later cut-off times as a result of the new faster transport option;
- Freight operators may choose to change their warehousing strategy due to the shorter transport time;
- Local public transportation options well-connected to the Hyperloop system may increase their usage by passengers who need the local accessibility option.

Several additional operational impacts are expected to arise but are unknown at this time.

5.6.3 Organizational impacts

Numerous organizational impacts are foreseen for operating Hyperloop systems. Those which have been identified to date include:

- Significant hiring and organizational scale-up for research and development, manufacturing, operations, maintenance, etc.;
- Commitment of resources to lead the development of each regional system;
- Need for information sharing and collaboration between teams working in various organizations involved across regions and countries, to ensure that each Hyperloop system will be based on the relevant lessons learned to date across the respective developers;
- Need for learning and training to ensure that staff members will be properly trained to carry out their responsibilities.

Several other currently unforeseen organizational impacts are expected to arise.

5.6.4 Construction Impacts

The process of developing and constructing a Hyperloop system will itself have numerous impacts. These are expected to include:

- Additional land will be required during the construction phase, for access roads, machinery, etc.; this land should be restored to its original state, whenever possible, once construction is completed;
- Materials used to construct the Hyperloop system will have their own impacts (e.g. concrete is known as a significant source of CO₂ emissions); therefore, they should be selected with negative impacts in mind, to minimize them whenever possible and apply the decarbonisation process for the manufacturing of carbon-intensive raw materials, such as steel or cement (New Climate Institute, 2020);
- Materials to be transported from the fabrication/manufacturing site to the construction site will create an additional burden on current infrastructure, such as roads, until the construction is completed; therefore, research are started in collaboration with the Hyperloop promoters to tackle this issue, by approaching new manufacturing processes to reduce the transportation burden;
- Development of the innovative system will necessitate dedicated training activities and a significant supply chain and will therefore provide a large economic boost.

Other impacts, not yet considered, are expected to arise from the construction development.

6 Conclusions

The present Deliverable summarized the activity developed within the Work Package 3, dealing with the *Technical Definitions* that populate the different scenarios of the start-up process of Hyperloop. In the general spirit of the HYPERNEX project all the technical analysis had an eye to what is possible to accept and adapt from the rail know-how and integrate with the present developments and the ongoing programs in the other transport modes within a large intermodal vision.

The Deliverable is composed of four main sections, respectively dealing with: 1) innovative concepts suitable for guided transport modes; 2) hazards identification and safety cases analysis; 3) technical components of Hyperloop architecture; 4) Hyperloop operation concept.

Section 1 explored innovative guided transport modes and examine their architectural, functional and legislative aspects. The guided transport concepts explored and compared are Hyperloop, Maglev, Aviation and High-Speed Rail. Different use cases of transport modes, such as freight or passenger, were touched upon. A scalability analysis of capital and operational expenses analyses has been conducted and an overview of transport innovations has been articulated, including expected future developments and more energy efficient transport alternatives and depicting standardization and homologation perspectives. The results of this section created the basis for high level transport planning analyses aimed at selecting the best transport mode for defined market segments and, mutually, the best application fields for the innovative guided transport modes, such as Hyperloop.

Section 2 explored the required safety requirements and checks in a systemic view based on the established methodological framework to be considered in a homologation and certification perspective. The reference were Safety Common Methods (SCM) and EN 50126 schemes. Safety have been carefully identified with a close connection both with the technical components and the operational modes involved. The analyses referred to a generic Hyperloop system and the discussed hazards common were those common to all Hyperloop solutions, which have been classified by the evaluations of probability and consequences. At the present level of knowledge, it was obviously a wide generic case hazard analysis qualified by the description of safety cases and the identification of missing information on components and operational parameters, which is the most important added value brought by the feedback of this section.

Section 3 analysed a large number of technical elements of the Hyperloop systems' architecture and subsystem components, but frequently the analyses were forced to maintain a level of definition compatible with the knowledge basis, which for various components is still at the pure system engineering principles and concepts. The technologies envisaged as exportable to Hyperloop from more consolidated transport modes have been highlighted in this chapter. For the less mature or less defined technical components, a number of further research areas have been identified, particularly for those depending on the integration of Hyperloop into current and future spatial planning policies and transport network developments. Nevertheless, discussions on the analysis of linear, non-linear, static, dynamic and buckling behaviour of the pipes, the optimal tube

diameter, tunnel infrastructures that would reduce environmental impacts, most appropriate acceleration and deceleration profiles, applicability of the existing communication systems for low pressure and high speed environments, vehicles platooning and headways in relation to safety as well as capacity and comfort of passengers. This section had not the ambition to cover deep technical aspects on components of a Hyperloop system that is far to be defined in its final architecture, but successfully activated the discussion on many key technical tables that should progressively find answers to the many still open questions at system, subsystem and components level.

Section 4 proposed operational concepts for future tube transportation systems designed to facilitate intermodal connections with other passengers transport systems and freight delivery services. The focus was on the specifications by local transportation regulators and standardization bodies, depending on impacts on surrounding environment and nearby communities. Operational scenarios were depicted to identify potential issues to be considered within the design of the system in a typically multimodal approach and in a life cycle perspective, not excluding a safe decommissioning process at the end of the lifetime. The results of this section represent the basis for the definition of cost-effective design procedures aimed at the definition of the operational context for freight and passengers services aligned with the market segment, which will be identified as a consequence of the achievements in Section 1.

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8 Annex 1: High Speed Rail Definition according to Directive 96/48/EC

8.1 Infrastructure

a) The infrastructure of the trans-European High Speed system shall be that on the trans-European transport network identified in Article 129C of the Treaty:

- Built specially for High Speed travel,
- Specially upgraded for High Speed travel; they may include connecting lines, in particular junctions of new lines upgraded for High Speed with town centre stations located on them, on which speeds must take account of local conditions.

b) High Speed lines shall comprise:

- Specially built, equipped for speeds generally equal to or greater than 250 km/h,
- Specially upgraded, equipped for speeds around 200 km/h,
- Specially upgraded, which have special features as a result of topographical, relief or town-planning constraints, on which the speed must be adapted to each case.

8.2 Rolling stock

The High Speed advanced-technology trains shall be designed in such a way, as to guarantee safe, uninterrupted travel at:

- Speed of at least 250 km/h on lines specially built for High Speed, while enabling speeds of over 300 km/h to be reached in appropriate circumstances,
- Speed of around 200 km/h on existing lines which have been or are specially upgraded,
- The highest possible speed on other lines.

9 Annex 2: Hazard log including matrixes

This Annex includes the matrixes resuming system, subsystem, hazard description, hazard mitigation measures and results of the severity and occurrence analysis.

System	Sub-system	Function	#	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Guidance	Active lateral guidance	System responsible for creating the necessary attractive force that allows the high speed switches to function properly	H1	Communication failure	Active lateral guidance activates too late	C	Vehicle-Track and Pod-Pod collision	1	C1	Redundant communication system. Monitoring.	C	4	C4
			H2	Power outage	Not activation of active lateral guidance	D	Pod-Track and Pod-Pod collision	2	D2	Redundant power supply for the active lateral guidance.	D	4	D4
			H3	Magnets decay	Not enough pulling force of active lateral guidance	D	Pod-Track collision	2	D2	Monitor the operation of the magnets to detect any possible signs of failure. Carry out an adequate maintenance plan so that the magnets are in the best possible condition.	E	2	E2
	Switch	Mechanical track change similar to those of magnetic levitation trains	H4	Communication failure	Active lateral guidance activates too late	C	Pod-Track and Pod-Pod collision	2	C1	Redundant communication system. Monitoring.	C	4	C4
			H5	Power outage	Not activation of active lateral guidance	D	Pod-Track and Pod-Pod collision	3	D3	Redundant power supply for the active lateral guidance.	D	4	D4

System	Sub-system	Function	#	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Track	Physical element that serves as a guide for the pod	H6	Track misalignment	Collision pod with track	D	Pod-Track collision Pod damage	2	D2	Track condition monitoring to detect possible unexpected failures. Maintenance plan that allows the track to be in the most optimal conditions possible.	E	2	E2
			H7	System failure due to poor maintenance	The system is not in a condition to function properly	C	Pod-Track and pod-pod collision	1	C1	Establish a proper maintenance plan. Trained staff. Maintain an adequate safety distance. Prevent the activation of the change of track if there is a pod too close.	D	4	D4
			H8	An operator makes a mistake when giving the order to activate a track change	Order to activate the wrong track change	D	Pod-Track and pod-pod collision	1	D1	Trained staff. Maintain an adequate safety distance. Prevent the activation of the change of track if there is a pod too close.	E	3	E3

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Propulsion/Levitation	Linear Engine	System responsible for the propulsion of the pod	H9	Failure during acceleration	No sufficient speed	D	Pod unable to reach sufficient speed Pod-Pod collision	3	D3	LSM operation monitoring and maintenance plan. Communication to nearby pods of the fault to slow down.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
			H10	Power outage in LSM	LSM out of service	D	Pod slow down	3	D3	Redundant power supply and secondary propulsion system. Communication to nearby pods of the fault to slow down.	D	5	D5
			H11	Overcharging	Destroying part of the LSM	C	Pod Slow down Pod damage	3	C3	Design to withstand power abundance and segmentation of LSM. Communication to nearby pods of the fault to slow down.	E	4	E4
			H12	Communication failure	Pod is not propelled properly	C	Pod-Pod collision	2	C2	The communication system must be sufficiently tested to ensure that the information transmitted is correct. Redundant communication system	E	3	E3
	Magnets	Allow the pod to levitate over the tracks	H13	Pod too heavy	Decaying, small gap height	E	Pod-Track collision	3	E3				
			H14	Magnets decaying over time	Lower lift forces leading to smaller gap heights	D	Pod-Track collision	4	D4				
			H15	The levitation system is misaligned from the track	Misalignment of the levitation system	D	Pod-Track collision	2	D2	Levitation system monitoring to detect possible unexpected failures.	E	4	E4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Brake	System in charge of reducing the speed of the pod		due to possible bumps or installation errors						Maintenance plan that allows the magnets to be in the most optimal conditions possible.			
			H16	Energy cut	The pod is unable to brake	D	Pod-Track and pod-Pod collision	1	D1	Secondary power supply. Secondary emergency brake.	D	4	D4
			H17	Communication failure	The pod does not receive the brake order on time or receives it too soon	C	Pod-Track and pod-Pod collision	1	C1	The braking system should not depend on a single communication system. Secondary emergency braking system. Brake status monitoring.	E	4	E4
			H18	Electrical or mechanical fault in the brake	The brake is not able to use enough force to stop	C	Pod-Track and Pod-Pod collision	1	C1	Secondary emergency braking system. Brake status monitoring.	D	4	D4
			H19	System software error. Lack of information	The system is not capable of making a correct braking curve	C	Pod-Track and Pod-Pod collision	1	C1	Secondary communication system. Software sufficiently tested to confirm its operation.	E	2	E2
			H20	Lack of proper maintenance	The system is not in a condition to function properly	C	Pod-Track and Pod-Pod collision	1	C1	Establish a proper maintenance plan. Trained staff. Maintain an adequate safety distance.	D	4	D4
			H21	An operator in the control	Wrong activation of	D	Pod-Pod collision	3	D3	Trained staff. Adequate and	E	5	E5

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
				room or the driver accidentally activates the braking system	the braking system by the staff					operational communication system between pods.			
			H22	An operator in the control room or the driver accidentally activates the propulsion system	Wrong activation of the propulsion system by the staff	D	Pod-Pod and pod-Track Collision	2	D2	Set a maximum speed in each zone automatically. Adequate and operational communication system between pods.	E	4	E4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Energy supply	External Power Supply	Provides the energy necessary for the rest of systems to work	H23	Instability of the power supply	Temporary spike or drop in energy supply.	C	Damaged systems	3	C3	Different systems must have the necessary protections against sudden increases or decreases in voltage	D	4	D4
			H24	Instability of the power supply Power supply failure Sabotage	Energy cut	D	Pod Slow down and pod-Track collision	2	D2	Redundant power supply. Installation of internal power in the pod that allows it to continue operating until it reaches a safe state.	E	2	E2

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Auxiliary Power Supply	Provides the energy necessary for the rest of systems to work when the principal power supply fails	H25	Auxiliary system fails together with external	The systems do not receive the necessary energy	D	Pod Slow down Pod-Pod collision	2	D2	Periodic reviews of the status and correct operation of this auxiliary power supply.	E	2	E2
	Solar Panels	Provides power to the systems supporting the other power sources.	H26	Solar panels failure due to lack of maintenance or external causes such as storms	Not enough power for all systems	B	Pod Slow down Pod-Pod collision	4	B4				
	Induction Loop	System responsible for supplying power to the pod without contact. It is the alternative to using batteries.	H27	Energy cut. Malfunction.	The pod is not receiving enough power to run	D	Pod-Track collision	2	D2	Secondary power batteries. Unfolding the wheels to avoid collision with the road.	D	4	D4
	Subsystem power supply	Transmits the energy to the corresponding subsystems	H28	Damaged cable due to not being properly protected or poor maintenance	Corroded cable	D	Pod-Pod and pod-track collision	1	D1	Carry out periodic reviews of the condition of the cables. Monitoring	E	3	E3

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Subsystem power supply	Transmits the energy to the corresponding subsystems	H29	Cables located in an area where they are not protected or that due to maintenance or external damage have been exposed	Unprotected or exposed cable	D	People injury/death	1	D1		E	4	E4
			H30	Power outage or power transmission failure (damaged cables)	Magnetic levitation motor does not receive the necessary energy. Variation of the gap between the pod and the track	D	Pod-track collision	1	D1	A system must be in place that allows the wheels to be deployed quickly in case the distance between the pod and the track decreases too much	D	4	D4
			H31	Power outage or power transmission failure (damaged cables)	Braking system does not receive the necessary energy	D	Pod-Pod collision	1	D1	Redundant power supply or an alternative braking system that operates isolated	D	4	D4
			H32	Power outage or power transmission failure	Switch does not receive the necessary energy	D	Pod-Track and pod-pod collision	1	D1	Redundant power supply	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
				(damaged cables)									
			H33	Power outage	Tube does not receive the necessary energy for all the systems	D	Pod-track collision and loss of communications	2	D2	Redundant power supply	D	4	D4
			H34	Power outage	Stations does not receive the necessary energy for all the systems	D	Service interruption and loss of communications	3	D3	Redundant power supply	D	5	E5
	Stationary energy distribution and storage	System in charge of storing energy and distributing it	H35	Failure in the heat dissipation systems produced by the different electrical systems	Thermal storage is not adequate and the pod begins to heat up	C	Passenger's discomfort Fire in the pod and the tube	2	C2	Temperature sensors must be installed in areas with a greater tendency to heat up and if this exceeds a certain threshold, send an alert to stop the service. The system in charge of heat dissipation must be severely tested to verify its correct operation.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
			H36	There is an error in the connection of the hoses or the liquid reserves in the station are exhausted and the cooling system cannot work if the liquid is not renewed by another cold	The connections for the renewal of the coolant in the stations fail.	D	The pod cannot start until the liquid is renewed	4	D4				
			H37	The cooling system is not well sealed and there is a leak of the coolant in the pod	Coolant leak	D	The coolant can reach other electronic systems, damaging them and causing them to fail.	1	D1	The battery cooling system must be isolated from the rest of the systems, so that in the event of a leak it cannot damage them. Circuit pressure monitoring system. Adequate maintenance plan.	E	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
			H38	The battery charging system in the stations is not operational or an error occurs due to a bad connection that does not allow charging to be carried out at the appropriate speed.	Batteries are not charging or charging is too slow	D	The pod cannot leave the station if it does not have the proper battery level	4	D4				
			H39	When carrying out the change of the batteries they connect badly to the pod due to an error of the operators or the new battery.	Replacing the batteries causes a bad connection of the same	C	The connection may not allow all the necessary power to reach the pod or it may be disconnected in the middle of the journey.	2	C2	All the batteries that are in the reserve stations must have passed a control that ensures that they are in good condition. Those in charge of changing the batteries must have adequate training and conditions. The battery connection system			E4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										must not play, allowing only one position in which the battery fits. Secondary batteries for the main systems that allow the pod to circulate to a safe zone in the event of failure.			
			H40	There are no charged batteries available in the station, or the replacement system fails.	Batteries cannot be replaced	D	The pod cannot leave the station if the change is not made.	4	D4				
			H41	Pod batteries stop working due to poor battery condition, connection failure, or overheating	The pod batteries stop feeding the pod systems, such as communications, propulsion, braking, ...	C	Pod Slow down Pod-Pod collision Fire in the pod	1	C1	Use batteries with a sufficiently proven technology to try to minimize the possibility of fire or failure. Installation of systems that constantly monitor the temperature of the batteries and that if it increases	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										too much they send an alert			
			H42	Lack of maintenance or improper maintenance	The system is not in condition to function properly	C	Pod Slow down Pod-Pod and pod-Track collision	1	C1	Establish a proper maintenance plan. Trained staff. Secondary power batteries.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Communication system	Main communication system	System in charge of transmitting the needs and orders from one subsystem to another	H43	Data Management System fails due to software or external failures	Frequency The system is not able to process in time all the data it receives	C	Pod-Pod and Pod-Track Collision Pod goes too slow or too fast	2	C2	The communication system must be proven that it is capable of processing all the information that it would receive while in normal operation. The balises and other road elements that communicate with the pod will be at a sufficient distance to be able to	E	4	E4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										process all the information.			
			H44		Reliability Communication occurs but the transmitted data is not correct	D	Pod-Pod and Pod-Track Collision	1	D1	The communication system must be sufficiently tested to ensure that the information transmitted is correct.	E	3	E3
			H45		Availability The communication systems are not available due to some error and could not be restored	D	Pod-Pod and Pod-Track Collision	3	D3	The designer of the communication system must design it taking into account repair times, trying to ensure that these are the least possible. Making the parts most likely to fail are easily replaceable with a new one. The MTBF of the system should also be as high as possible to avoid repair downtime.	D	4	D4
			H46	Communication Signal delay due to	Pod-Pod communication fails	D	Pod-Pod Collision	1	D1	The communication system between pods must be sufficiently tested	E	3	E3

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
				interference or system failures						and optimized to minimize order delays. Secondary communication system between the main subsystems capable of operating in an emergency. Low latency communication system.			
			H47		Pod-Infrastructure communication fails	D	Pod unable to switch tracks	1	D1	The communication system must be sufficiently tested and optimized to minimize order delays. Secondary communication system between the main subsystems capable of operating in an emergency. Low latency communication system.	E	3	E3

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
			H48		Pod-Control communication fails	D	Pod Brakes too early or too late	1	D1	The communication system must be sufficiently tested and optimized to minimize order delays. Secondary communication system between the main subsystems capable of operating in an emergency. Low latency communication system.	E	3	E3
			H49	The system is hacked and communications are compromised	Data security is compromised and they are no longer reliable	D	Pod-Pod and Pod-Track Collision	1	D1	The communication system must have protection barriers against hacks. These barriers must make the system very difficult to hack and in the event of an attack, they must produce an alert to notify the personnel and take the appropriate actions. Continuous monitoring of the	E	4	E4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										communication system. Secondary communication system between the main subsystems capable of operating in an emergency			
	Location sensors	Determinates the position of each pod and transmit it to the control center	H50	Location sensors in tube fails	Unreliable pod location	D	Pod-Pod Collision	1	D1	Maintenance plan for the position sensors to verify their operation. Monitoring.	E	2	E2
			H51	Location sensor out of service	No data of pod location	D	Pod-Pod Collision	1	D1	Maintenance plan for the position sensors to verify their operation. Monitoring.	E	2	E2
	Monitoring system	Subsystem in charge of monitoring the status of the different hyperloop equipment, and alerting in the event of any failure	H52	Failure in the transmission of information from the different sensors or alert that one has failed	Full or partial failure of network monitoring equipment	D	The status of the various equipment of the subsystems cannot be determined	2	D2	Secondary communication system.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
			H53	Lack of maintenance or improper maintenance	The system is not in condition to function properly	C	Pod-Pod and Pod-Track Collision	1	C1	Establish a proper maintenance plan. Trained staff. Secondary communication system.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Communication Interfaces		Interfaces between the different subsystems to keep them in contact so that they can work in a synchronized way when necessary	H54	The interface between the energy subsystem and the other subsystems fails, so they do not receive the energy they need	Subsystems, such as propulsion, levitation, control, communications ... cannot function without electrical energy	C	Pod-Pod and pod-Track Collision	2	C2	If a system loses power, an alert must be issued to inform the personnel on board the pod and the control center, so that the appropriate emergency systems can be activated (auxiliary power, emergency brake, wheel deployment ...). Maintenance plans must be carried out strict enough to prevent this situation from	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										occurring or to reduce it to the minimum possible.			
			H55	The system is not able to define the proper braking curves due to software failures, in communication ...	The system is not capable of defining an adequate braking curve according to the characteristics of the track	C	Pod-Track Collision	1	C1	The information from the signalling system that the pod receives must be sufficient for it to determine a suitable braking curve. Operational tests must be carried out under different circumstances to ensure the correct operation of the system. Redundant communication system between the track and the pod to ensure that it receives the necessary information.	E	2	E2
			H56		Brake dynamic control Information on	C	Pod-Pod Collision	1	C1	Operational tests must be carried out under	E	2	E2

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
					the location of the front pod's tail and its speed or next moves is not available, or this information is not entirely accurate. Due to this, the pod speed or the braking curve cannot be modified.					different circumstances to ensure the correct operation of the system. Redundant communication system between the pods to ensure that it receives the necessary information.			
			H57	Interference between systems, or communication failure	The interface between the track signalling and the pod is not adequate	B	Pod-Pod and pod-Track Collision	1	B1	Secondary communication system. Constant monitoring of communications. Sufficiently tested interface.	D	4	D4
			H58	Interference between systems, or communication failure	The interface between the control room and the pod is not adequate	C	Pod-Pod and pod-Track Collision	1	C1	Secondary communication system. Constant monitoring of communications. Sufficiently tested interface.	D	4	D4

System	Sub-system	Function		Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Control & Command		This system is in charge of controlling the operation of the other subsystems and of giving them the appropriate orders at the correct time.	H59	The control system is disabled due to an external computer attack	Hacked system	D	Pod-Pod and pod-Track Collision	1	D1	Cybersecurity systems that provide protection and alert staff in the case of an attack. Redundant control system.	E	4	E4
			H60	The system does not process orders properly	Software failure	D	Pod-Pod and pod-Track Collision	1	D1	The command system software must be tested and reliable enough to ensure that all orders are processed properly in the required time. The use of different redundant systems or components can be a good option.	E	3	E3
			H61	An error occurs due to a hardware failure, either due to lack of maintenance or sabotage	Hardware failure	C	Pod-Pod and pod-Track Collision	1	C1	The components of the control system must be robust enough so that an error due to physical failure does not occur. Systems must be protected against tampering so that they cannot be manipulated from the outside without the proper	E	4	E4

System	Sub-system	Function		Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										permissions. An adequate maintenance plan must be created that checks the correct condition of the equipment and replaces it when it is reaching the end of its useful life. The use of different redundant systems or components can be a good option, especially in more critical areas of the route.			
			H62	Some operator in the control room activates one of the track changes without this being planned.	Wrong activation of the change of track by the staff	D	The pod is on the wrong route Pod-Pod and pod-Track Collision	1	D1	Trained staff. Maintain an adequate safety distance. Prevent the activation of the change of track if there is a pod too close.	E	3	E3
			H63	An operator in the control room or the driver accidentally activates the	Wrong activation of the braking system by the staff	D	Pod-pod collision	3	D3	Trained staff. Adequate and operational communication system between pods.	E	5	E5

System	Sub-system	Function		Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
				braking system									
			H64	An operator in the control room or the driver accidentally activates the propulsion system	Wrong activation of the propulsion system by the staff	D	Pod-Pod and pod-Track Collision	2	D2	Trained staff. Adequate and operational communication system between pods. Automatic setting of the maximum speed at certain points of the route.	E	4	E4
			H65	Lack of maintenance or improper maintenance	The system is not in a condition to function properly	C	Pod-Pod and pod-Track Collision	1	C1	Establish a proper maintenance plan. Trained staff. Secondary control system.	D	4	D4
			H66	Lack of a protocol for action in an emergency	The response to a specific threat is not defined; this can lead to not knowing what to do at that time to solve it.	E	Pod-Pod and pod-Track Collision	2	E2				

System	Sub-system	Function		Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
EMC		It is responsible for verifying that the different installed electronic systems are capable of working correctly at the same time without causing interference between them or damage to people.	H67	The different subsystems produce interferences with each other causing them not to work properly	Electromagnetic interferences between systems	B	Pod-Pod and pod-Track Collision	1	B1	Take into account standards such as EN 50121 for emission and immunity limits when designing systems and perform tests to verify that there is no interference	E	3	E3
			H68	Generation of induced voltages in an area accessible by people	Damage to people's health	C	People injury	1	C1	Take into account standards such as EN 50121 for emission and immunity limits when designing systems and conducting tests to verify that induced voltages are not produced	E	2	E2

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Pod	Oxygen and pressure supply	Provide air pressure and oxygen to the passengers	H69	Pressure supply failure	Drop in cabin pressure	D	People injury/death	1	D1	Oxygen masks for passengers. Maintenance labors.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
			H70	Oxygen supply failure	No oxygen supply	D	People injury/death	1	D1	Additional oxygen tank, control system, oxygen masks, emergency exits. Maintenance labours.	D	4	D4
			H71		Oxygen leak in pod	D	People injury/death	1	D1		D	4	D4
			H72		Oxygen tank explosion	D	People injury/death	1	D1		D	4	D4
	External structure	Provide structural stiffness to the pod	H73	Excessive load > deformation > pressure leak	Passengers get exposed to vacuum environment	D	People injury/death	2	D2	Design with safety factor, oxygen tank, oxygen masks, emergency exit, leaks	D	4	D4
			H74		Crack creations	C	People injury/death Infrastructural damage	3	C3		D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										detection system			
			H75	Vibrations		B	Passenger discomfort	5	B5				B5
	Vacuum container		H76	Cracks and leaks		C	People injury/death. Infrastructural damage	3	C3	Leak system detection. Maintenance works.	D	4	D4
	Heating, Ventilation & Air Conditioning (HVAC) equipment	Provide a comfortable temperature to the passengers	H77	Air conditioning failure	Pod interior cannot be heated	C	Passenger discomfort	4	C4	Redundant HVAC system	D	5	D5
			H78	Heating failure	Pod interior cannot be cooled	E	Passenger discomfort	3	E3		E	4	E4
	Lightning system	Lighting system of the pod	H79	Mal functioning of the lighting system	No light/blinking lights in the pod	C	Passenger discomfort	5	C5	Emergency lighting	C	5	C5
	Fire Suppression & Detection (FSD)	Extinguish fire in pod	H80	Fire extinguishers failure	Fire in pod cannot be extinguished	D	People injury/death. Infrastructural damage. Infrastructural damage	1	D1	Periodical reviews of FSD system	D	4	D4
	Emergency system		H81	Emergency system failure	Emergency alarms do not work	D	people injury/death	1	D1	Periodical reviews of emergency system	D	5	D5

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Doors	Allow passengers enter/exit and seal the pod interior	H82	Door seal failure	Drop in cabin pressure	D	People injury/death	3	D3	Cabin pressure sensors and periodical reviews. colocación de sensores para monitorear el estado actual del sellado de las puertas	D	4	D4
		Evacuation doors	H83	door open/close system failure	Unable to carry out passenger evacuation	D	People injury/death	1	D1	Evacuation doors. Periodical reviews	D	4	D4
	Seats	Belts	H84	Mal functioning		D	People injury/death	3	D3	Periodical review of the belts	D	4	D4
	Propulsion and breaking from interior		H85	Pod unable to brake		D	People injury/death. Infrastructural damage	1	D1	Emergency braking system	D	4	D4
			H86	Pod unable to accelerate	Pod stays stuck in tube	D	service interruption	2	D2	Redundant acceleration system	D	4	D4
	Electronics	Make electronic	H87	Short circuiting of electronics	Fire in the pod	D	People injury/death.	3	D3	Incorporate exclusive FPS for electronic	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
		components work					Infrastructural damage			system (without water). Sensors			
			H88		Components are not working	D	service interruption	3	D3	Redundant electronics system. Operator training in electrical risk solution. Sensors	D	4	D4
	Batteries	Energy supply to the pod	H89	Excessive heating	Battery explosion/fire	D	People injury/death. Infrastructural damage	1	D1	cooling batteries and temperature sensors	D	4	D4
			H90	Explosion	Battery explosion	D	People injury/death. Infrastructural damage	1	D1	periodically check the status of the batteries, control BMS system	D	4	D4
	Low speed wheels	Provide traction at low speeds and support in case of power loss	H91	Deployment failure	Low speed wheels do not deploy	D	People injury/death. Infrastructural damage	3	D3	Constant monitoring of current system status	D	4	D4
			H92	Retraction failure	Low speed wheels do not retract	D	People injury/death. Infrastructural damage	3	D3	Constant monitoring of current system status	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Sensors and positioning		H93	Incorrect data collection	The pod becomes uncontrollable	D	People injury/death. Infrastructural damage	2	D2	Redundant sensor and control system. Employee training.	D	4	D4
	Control system connection		H94	Lose connection	imposible conectar con el sistema de central de control	D	People injury/death. Service interruption	3	D3	Secondary connection system	D	4	D4
	Noise		H95	Noise pollution	Environment disturbance	B	Environment disturbance	4	B4				B4
			H96		neighbourhood residents annoyance	C	neighbourhood residents annoyance	4	C4				C4
			H97		passenger discomfort	D	passenger discomfort	4	D4				D4
	Entertainment& information		H98	System failure	Prevent movie watch, music, entertainment availability, etc.	D	Passenger discomfort	5	D5				D5
	Tunnel		Tube	Provide structural stiffness, contain vacuum, supports track,	H99	Structural damage (corrosion, puncture, crack)	Leak in tube	C	Infrastructural damage	3	C3	Design with safety factor .. Maintenance works	D
H100		Structural failure			Tube deformation over serviceability limit state (SLS)	D	People injury/death.	3	D3	Design with safety factor.	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
		transports power					Infrastructural damage			Maintenance works			
			H 101		Tube deformation over ultimate limit state (ULS)	D	People injury/death. Infrastructural damage	1	D1	Design with safety factor. Maintenance works	D	4	D4
			H 102	Weld/bolt joints failure	loose screws, weld wear	D	People injury/death. Infrastructural damage	3	D3	Periodic checks	D	4	D4
			H 103	Presence of objects obstructing the tube	Obstruction in the pod way	D	People injury/death. Infrastructural damage	2	D2	Sensors and presence control inside the tube	D	4	D4
			H 104	People trespassing into the tube		E	People injury/death. Infrastructural damage	1	E1	Restrict tube access	E	4	E4
	Pylons	Support the tube, absorb vibrations	H 105	Pylon structural deformation	Tube deformation	D	People injury/death. Infrastructural damage.	1	D1	Design with safety factor and maintenance work	D	4	D4
	Track	Provide pod guidance	H 106	Track deterioration	Track excessive irregularities/misalignment	D	People injury/death. Infrastructural damage	2	D2	Design with safety factor and maintenance work	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Vacuum pumps	Create and maintain vacuum inside tube	H 107	Pump failure in tube	Inability to maintain vacuum at tube	C	People injury/death	3	C3	Backup compressor	C	4	C4
			H 108	Pump failure in airlock	Air flow to the tube	C	People injury/death	3	C3	Backup compressor	C	4	C4
			H 109	Pump overheating	Pump explosion in tube	D	People injury/death. Infrastructural damage	2	D2	Refrigeration and temperature sensors. Periodically check the status of the pumps, BMS control system. FP system	D	4	D4
			H 110		Pump explosion in airlock	D	People injury/death. Infrastructural damage	2	D2	Refrigeration and temperature sensors. Periodically check the status of the pumps, BMS control system. FP system	D	4	D4
			H 111	Power outage	No working pumps	C	People injury/death.	2	C2	Redundant power supply	C	4	C4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
							Service interruption						
	Rails		H 112	Deformation, deterioration, etc.	low speed wheels deployment failure	D	People injury/death. Infrastructural damage. Service interruption	3	D3	Maintenance work	D	4	D4
	Tube joints	Join different tube sections	H 113	Tube joints failure	Tube deformation	D	People injury/death. Infrastructural damage	2	D2	Design with safety factor. Maintenance work	D	4	D4
	Cabling	Power transport to pod	H 114	Cable damage	Inability to transmit power	C	service interruption	2	C2	Redundant system. Maintenance work	C	4	C4
			H 115		Inability to decelerate the pod using motors	C	Service interruption. People injury	2	C2	Include emergency brakes. Maintenance work	C	4	C4
			H 116	Cabling defect	Unprotected cable	E	People injury/death	1	E1	Include ground brake and protect cables. Periodic reviews and maintenance work	E	3	E3

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Switch	Allow pod to switch from one track to another	H 117	Switch failure	Pod unable to make the switch	D	People injury/death. Service interruption	2	D2	Control the passage of the pods depending on whether the switch has been made	D	4	D4
			H 118	Magnetic force debilitation	Not enough force for lateral guidance	D	People injury/death. Service interruption	2	D2	Redundant system.	D	4	D4
			H 119	Communication failure	Lateral guidance late activation	C	People injury/death. Service interruption	2	C2	Redundant communication system	C	4	C4
			H 120	Power outage	Lateral guidance does not activate	D	People injury/death. Service interruption	2	D2	Collision avoiding switch design and redundant power supply	D	4	D4
			H 121	Vibrations		C	Passenger discomfort	4	C4	Dampers	C	5	C5

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
Terminal	Airlocks	Transfer pods from atmospheric pressure in terminals to near vacuum pressure in tubes and vice versa	H 122	Airlock gate failure	Airlock door unable to open/close at tube/terminal side	C	Service interruption	3	C3	Just one door can be opened at any time, multiple airlocks at terminal	C	4	C4
	Boarding/aligning equipment	Allow passengers transfer from terminal to pod and vice versa	H 123	Boarding/aligning equipment failure	Boarding/aligning equipment does not work properly	C	service interruption	4	C4	Maintenance work	C	4	C4
	Pod load/unload system	Loads/unloads pods for travel	H 124	Pod load/unload equipment failure	Pod load/unload equipment does not work properly	D	service interruption	2	D2	Redundant load/unload equipment system. Maintenance work	D	4	D4
	Building		H 125	Collapse	The structure gives way	E	People death	1	E1	Design with safety factors. Maintenance works.	E	4	E4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Docking services		H126	Failure in coupling at docking point	Inability to download	C	Service delay	4	C4	Use of sensors and signalling to ensure the correct positioning of the capsule when loading and unloading.	C	4	C4
	Passenger flow control		H127	Bad design of passengers flow	crowds of people or difficulty moving around the terminal	C	People injury	5	C5				C5
	Integration with existing infrastructures		H128	Integration with other infrastructure systems like, airports, roads, stations	Interferences between means of transports and others	D		4	D4				D4
	Elevators, fixed mechanical escalators		H129	Passengers injuries		C	People injury	3	C3	Signs with use instructions to avoid accidents. Fluorescent lights	C	4	C4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Emergency exits		H 130	Inaccessible emergency exits		D	People injury/death	2	D2	Surveillance system that verifies that they are accessible	D	4	D4
	FP system		H 131	Fire		D	People injury/death	2	D2	Periodical review of the FP system.	D	5	D5
	Platform		H 132	Excess passengers on the platform		B	People injury/death	3	B3	Passenger flow system design. Give information to passengers on how to circulate through the station.	B	4	B4
Signalling	vehicle detection systems	Dynamics & positioning	H 133	Vehicle position detection error		D	service interruption. People injury	1	D1	Use low latency systems (fiber, etc). Auxiliary location system	D	4	D4
		stopping point protection	H 134	Error in the pod expected stopping point	The capsule does not stop where it should	D	People injury/death	1	D1	System that prevents the pod from passing from	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
		Routing (detours)								the area where it should brake.			
			H 135	Movement blockage		D	People injury/death	1	D1	Prevent the pod from continuing to advance if the detour has not been made. Maintenance work	D	4	D4
			H 136	End of stroke detection	The system that detects if the tracks are in their correct position stops working.	D	People injury/death	1	D1	Prevent the pod from continuing to advance if the detour has not been made. Maintenance work	D	4	D4
			H 137	Blocking system failure	Tracks are not well fixed	D	People injury/death	2	D2	Prevent the pod from continuing to advance if the detour has not been made. Maintenance work	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Interlocking	authorization system for the passage of control signals, location of the train position by track circuits	H 138	End of track protection		D		1	D1	Prevent the pod from continuing to advance if the detour has not been made. Maintenance work	D	4	D4
			H 139	Access coordination (control)		D	people injury/death	1	D1	Redundant control system / offline control system or a software that does with the information until the moment of the trip, makes a prediction of where the pod should go. Search connection by other means (i.e infrared)	D	4	D4
			H 140	Interlocking compatibilities		D	people injury/death	1	D1	Redundant communication	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										n system. Periodic review of the system			
			H 141			D	service disruption/delay	2	D2	Redundant communication system. Periodic review of the system	D	4	D4
			H 142			D	Passenger discomfort	4	D4		D	4	D4
	Sensors		H 143	Broken sensors		C	People injury/death	2	C2	Periodical review	C	4	C4
Environment	Physical environment	Weather	H 144	Extreme weather conditions	Extreme heat	B	Infrastructural damage	3	B3	Weather forecast in each zone to foresee deformations	B	4	B4
		Earthquakes	H 145	Natural disasters	Earthquake	D	Infrastructural damage	1	D1	Build on non-seismic zone, design with anti-earthquake structure	D	4	D4
		Floods	H 146		Floods	D	Infrastructural damage	2	D2	Build in an area where	D	4	D4

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
										floods are not expected			
			H 147		Storm Rays	D	Infrastructural damage	2	D2	Lightning rod	D	4	D4
			H 148		Storms	B	Infrastructural damage	2	B2	Make the system resistant	B	4	B4
	Electrical supply		H 149			C	Service interruption	2	C2	Auxiliary supply system	C	4	C4
	Internet	server system and cabling	H 150	System failure		D	Service interruption	2	D2	Auxiliary communication system that works without internet connection	D	4	D4
	Regulations	Rules and laws restricting activity	H 151	Limitations of the hyperloop system		C	Service interruption	4	C4				C4
	Non authorized interventions		H 152	Terrorist attack, major failure		E	people injury/death	1	E1				E1

System	Sub-system	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
	Close infrastructures		H 153	Interference from other nearby infrastructures	Interferences, vibrations, etc.	D	people discomfort	4	D4				D4
	Nature	Occupied area	H 154	Natural environment encroachment		B	environmental nuisance	4	B4	Doing a preliminary study of the location of the hyperloop and adapting to it	B	4	B4

System	Subsystem	Function	ID	Causes	Hazard description	Occurrence	Consequences	Severity	Result	Hazard mitigation	Occurrence	Severity	Result
On-board propulsion	Fan ingestion	Generate thrust by compressing it	H 155	Foreign Object Debris (FOD) ingested by the compressor		D	Major damage to the system, and potentially to the cabin	2	D2	Periodical review. Sensors to detect FOD	E	4	E4

10 Annex 3: Standards and regulations

The standards and regulations used to support the Hyperloop Operation analyses are described in the following sections.

For the hyperloop line, the following standards in the aerospace, rail and aviation industries may be applicable. This is not an exhaustive list and certain standards listed may be deemed irrelevant in the future based on further analysis.

Aerospace		Rail	Aviation
ECSS-E-ST-10-03C	CEI 249-2	PR NF EN 62477-2	Ch2_ED-14D_published
ECSS-E-ST-10-06C	CEI 249-3-3	NF C 20-730	RTCA DO-160G
ECSS-E-ST-20C	CEI 270	NF C 86-410	ED-80-RTCA DO 254
ECSS-E-ST-31C	CEI 321	NF C 93-050	EUROCAE ED-12B_published / DO 178
ECSS-E-ST-32C	CEI 321-2	NF C 93-427	pr NF EN 61508-1
ECSS-E-ST-40C	CEI 326-3	NF C 93-522	pr NF EN 61508-2
ECSS-E-ST-50C	CEI 352-1	NF C 93-713	pr NF EN 61508-3
ECSS-E-ST-10C	CEI 364	NF C 93-751	pr NF EN 61508-4
ECSS-E-ST-10-02C	CEI 603-2	NF C 96-410	pr NF EN 61508-5
ECSS-E-ST-20-07C	CEI 61373	NF F 01-305	pr NF EN 61508-6
ECSS-E-ST-32-02C	CEI 755	NF F 16-101	pr NF EN 61508-7
ECSS-E-ST-32-08C	CEI 801-5	NF F 16-102	
ECSS-E-ST-10-04C	CEI 898	NF F 16-103	
RNC-CNES-Q-60-511-E-A	CEI 97	NF F 61-010	
RNC-CNES-Q-60-514-E-A	IEC 60077-1:2017	NF F 61-014	
RNC-CNES-Q-60-515-E-A	IEC 60077-2:2017	NF F 61-032	
RNC-CNES-Q-60-516-E-W	EN 50128	NF F 63-295	
RNC-CNES-Q-60-517-E-W	EN 50129	NF F 63-307	
RNC-CNES-Q-60-518-E-A	EN 50153	NF F 63-436	
RNC-CNES-Q-60-520-E-W	EN 50155	NF F 63-826	
RNC-CNES-Q-60-521-E-A	NF EN 61287-1	NF F 63-827	
RNC-CNES-Q-60-522-E-A	NF EN 60947-1	NF F 70-010	
RNC-CNES-Q-70-506-E-A	NF EN 60947-5-1	NF F 74-001	
RNC-CNES-Q-70-508-E-A	EN 50163	NF F 74-101	
RNC-CNES-Q-70-510-F-A	NF EN 62262:2004 BS EN 62262:2002	pr NF EN 61347-2-8	
PD IEC/TS 62672-1:2013	NF EN 60068-2	NF EN 50306-1:2003	
EN 50261	pr EN 50121-3	NF EN 50306-2:2003	
pr EN 50126	pr EN 50124-1	NF EN 50306-3:2003	
	pr EN 50125-1	NF EN 50306-4:2003	
		ST SNCF n° 273	
		ST SNCF/RATP STM-S-001	



Hyperloop systems do not lay under the responsibility of a specific European Agency (EASA, ERA, ESA, etc.), nor to a specific agency elsewhere around the world (e.g. NASA, US Department of Transportation, etc.).

A European Agency specific to Hyperloop systems is not under development. As of today, Hyperloop regulation is being considered by Shift2Rail Joint Undertaking and the Directorate-General for Mobility and Transport (DG MOVE) of the European Commission. Therefore, for the Hyperloop system's regulation, the following study has been drafted: *Study on a regulatory framework for Hyperloop, an innovative transport technology, performed for DG MOVE under the Specific contract MOVE/C4/2020-85 during the period from July 2020 to March 2021.*

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