A Hyperloop Handbook for Public and Private Stakeholders

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DELFT HYPERLOOP

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Executive Summary

The hyperloop is a new high-speed transportation concept that uses a network of near-vacuum tubes in which vehicles, pods, travel. These pods use (electro)magnets to move and levitate, reducing resistance forces. The hyperloop can therefore travel with 1000 km/h with minimal electrical energy consumption. The hyperloop concept is, for this reason, often named as a solution to finding a sustainable way of fast transportation, which is needed to reduce emissions caused by the transportation sector.

The most challenges that the hyperloop still faces before implementation, lie in the social and economic aspects and the decision-making process of investors and other stakeholders. This handbook aims to give stakeholders, and especially the commissioning parties, an overview of the possible stakeholder and project organization. Moreover, this report can help in the decision-making process by reviewing aspects of the hyperloop business case and discussing the expected social and economic effects. This way, this report could bring the European hyperloop network a bit closer to realization.

Principles of the Hyperloop System

In order to put the organization and decision-making process around the hyperloop project into perspective, first, it is important to understand how the hyperloop works and how it could fit in people's lives. The hyperloop concept uses pods that travel through a near-vacuum tube network. These tubes run either underground, on land or suspended on pillars. All systems run on electricity, meaning that if this energy is supplied by sustainable energy sources, a hyperloop network would emit no greenhouse or harmful gasses during operation. Hyperloop stations are expected to be located in or around large cities and will connect these with other cities at distances of 100 to 1500 km. Passengers will travel with the hyperloop inside a pod that is comparable with a single train coach in size and comfort.

Stakeholder Analysis and Participation Strategy

In the development of a European hyperloop network, a wide range of stakeholders is involved. This report views an overarching institution, assigned by the European Union, which initiates and authorizes the standardization and certification, as essential for uniting separate countries through a European hyperloop network. On a national level, three possible collaboration structures can be considered for organizing and implementing hyperloop development: a public commissioning party, a private commissioning party, or a combination of a public and private party. The latter can be expected to be most suitable for developing hyperloop infrastructure, due to the multidisciplinary nature and high investment costs of the project. The commissioning party should clearly distinguish the following five phases in the development of a hyperloop corridor: initiation phase, permitting phase, procurement phase, design and construction phase, and the operation and maintenance phase. Communicating with the involved parties, required actions and time frames of these phases with the relevant stakeholders is essential for collaboratively achieving the project goals within the set budget and time.

Business Case

For both public and private stakeholders, a hyperloop network needs to have a compelling business case. Hyperloop ticket prices need to be able to cover the capital, operational and maintenance costs within a certain return on investment time, while also being able to compete with ticket prices of competitors such as aviation and high speed rail. The capital costs of hyperloop are expected to be considerable, since an expensive tube network of hundreds of kilometers needs to be built before revenue can be generated through operation. Assessing the operational and maintenance costs is difficult and still many variables are unknown, since no operational hyperloop system has been built yet. Estimations can be made by comparing the operational and maintenance costs with those of similar types of transport. Demand is expected to come from three types of travelers: social recreational travelers, daily commuters and people going on business trips. The

hyperloop can take over (part of) the demand from its competitors, such as aviation, high speed rail and cars by proving to be more beneficial in terms of travel time savings, comfort and potentially ticket price. Revenue is generated through ticket sales and concessions at hyperloop stations. Revenue can also be generated through multi-use of infrastructure. Large infrastructure components such as the tube can provide additional space for other utilities such as sewers (when tubes are placed underground). In terms of the hyperloop's market position compared to car, bus, rail, high speed rail and aviation, the hyperloop has strong advantages in terms of speed, comfort and timeliness when applied to larger national and international distances.

Barriers in Hyperloop Development and Implementation

As a concept, the hyperloop still has barriers to overcome before implementation. The first is standardization. There are many different technologies that can be used in a hyperloop network. Different propulsion technologies require the use of different levitation technologies, meaning not every pod is compatible with every track. If multiple hyperloop parties build pods and tracks that are not compatible with the ones of competitors, pods from one country cannot travel through the tube of another. This negatively affects the operational efficiency of the network. International standards need to be set to avoid this. For a hyperloop network in Europe, the tubes will have to cross borders between countries as well as provinces/national regions. For a successful network, all the countries and regions through which the hyperloop tubes will run have to be on board with the network to allow for smooth legislation, spatial planning and politics. Lastly, a hyperloop network will be very costly due to the high capital costs. It requires an enormous investment from, most likely, multiple parties, either private, public or both.

External Effects and Social Merit

A hyperloop network also brings external effects and social merit. The travel time savings that the hyperloop offers could have an effect on employment and housing in and around cities with a hyperloop station. The hyperloop could also have an effect on traffic congestion when people switch from using cars to using the hyperloop. Due to the closed tube environment, accidents with external objects are less likely to happen. However, with the large operational speeds of the hyperloop, accidents such as collisions between pods and damages to the tube can prove to be fatal for passengers. Strict safety standards have to be set, that make sure that the hyperloop has at least the level of safety of aviation. A hyperloop network will also have environmental effects. Since the hyperloop can fully run on electricity, operation can be emission free when this energy is supplied by sustainable sources. However, manufacturing and constructing hundreds of kilometers of tube for the network will likely cause for large amounts of greenhouse gas emissions. This has to be taken into account when assessing the environmental effects of the hyperloop. The spatial effects of the hyperloop will depend on the vertical alignment of the tubes. Tubes can run underground, which adds to the capital costs due to tunneling, but avoids the negative spatial effects such as visual pollution and habitat loss. The tube can also run on the ground or above ground on pillars, decreasing capital costs of tunneling, but increasing the impact on habitat, visual pollution and land use.

Samenvatting

De hyperloop is een nieuw transportconcept dat gebruik maakt van vacuüm buizen waar voertuigen, genaamd ’pods’, doorheen bewegen. Deze pods gebruiken (elektro)mageneten om te zweven en zich voort te stuwen, waardoor luchtweerstand en rolweerstand geminimaliseerd worden. Hierdoor kunnen hyperlooppods met 1000 km/u zich voortbewegen met een minimale energieconcumptie. Het hyperloop concept wordt daarom vaak genoemd als een oplossing voor het vinden van duurzaam transport op hoge snelheid, wat nodig is om de uitstoot van de transportsector te verminderen.

De meeste uitdagingen waarmee de aanleg van de hyperloop nog geconfronteerd wordt, liggen in de sociale en economische aspecten en het besluitvormingsproces van investeerders en andere stakeholders. Dit handboek is bedoeld om stakeholders, en met name de toekomstige opdrachtgevers, een overzicht te geven van de mogelijke projectorganisatiestructuren. Bovendien kan dit rapport helpen bij het besluitvormingsproces door aspecten van de business case van de hyperloop te bespreken en in te gaan op de verwachte maatschappelijke en economische effecten. Op deze manier kan dit rapport een Europees hyperloopnetwerk een stukje dichter bij de realisatie brengen.

Beginselen van een Hyperloop Systeem

Om de organisatie en besluitvorming rond het hyperloop-project in perspectief te kunnen plaatsen, is het allereerst belangrijk om te begrijpen hoe de hyperloop werkt en hoe hij in de maatschappij zou kunnen passen. Het hyperloop-concept maakt gebruik van pods die reizen door een netwerk van vrijwel volledig vacuüm buizen. Deze buizen kunnen zowel onder de grond, op de grond als op pilaren boven de grond gebouwd worden. Alle systemen in hyperloopinfrastructuur werken op elektriciteit, dus als alle energie voor het systeem komt van duurzame bronnen, stoot de hyperloop geen broeikasgassen uit tijdens operatie.. Hyperloopstations zullen zich naar verwachting in of rond grote steden bevinden en deze verbinden met andere steden op afstanden van 100 tot 1500 km. Passagiers zullen met de hyperloop reizen in een pod die qua grootte en comfort vergelijkbaar is met een enkele treinwagon.

Stakeholderanalyse en Participatiestrategie

Bij de ontwikkeling van een Europees hyperloopnetwerk is een breed scala aan stakeholders betrokken. Dit rapport beschouwt een overkoepelende instelling, aangesteld door de Europese Unie, die de standaardisatie en certificatie initieert en autoriseert, als essentieel voor het verbinden van afzonderlijke landen via een Europees hyperloopnetwerk. Op nationaal niveau kunnen drie mogelijke samenwerkingsstructuren worden overwogen voor de organisatie en uitvoering van het hyperloop-project: organisatie vanuit een publieke opdrachtgever, een private opdrachtgever, of een combinatie van een publieke en private partij. Verwacht wordt dat de laatste het meest geschikt is voor de ontwikkeling van hyperloopinfrastructuur, vanwege het multidisciplinaire karakter en de hoge investeringskosten van het project. De opdrachtgevende partij moet duidelijk de volgende vijf fasen onderscheiden in de ontwikkeling van een hyperloopcorridor: initiatieffase, vergunningsfase, aanbestedingsfase, ontwerp- en bouwfase, en de gebruiks- en onderhoudsfase. Communicatie met de betrokken partijen, vereiste acties en tijdschema’s van deze fasen is van essentieel belang voor het gezamenlijk bereiken van de projectdoelstellingen binnen het vastgestelde budget en de vastgestelde tijd.

Businesscase

Voor publieke en private stakeholders is het belangrijk dat de hyperloop een gunstige businesscase biedt. Opbrengsten door de verkoop van hyperloopkaartjes moeten alle kapitale kosten, operationele kosten en onderhoudskosten kunnen dekken binnen een bepaalde ’return on investment’ tijd en daarnaast moeten ticketprijzen kunnen concurreren met de ticketprijzen van concurrenten zoals luchtvaart en hogesnelheidslijnen. Het wordt verwacht dat de kapitale kosten van de hyperloop substantieel zullen zijn door het aanleggen van honderden kilometers aan buizen voor een rendabel netwerk.

Het is lastig om de operationele kosten en onderhoudskosten van een hyperloopnetwerk te schatten, omdat er nog geen functionerend hyperloopsysteem bestaat. Schattingen worden gedaan door vergelijkingen te trekken met bestaande vormen van transport. Het wordt verwacht dat de vraag naar hyperloop zal komen van drie typen reizigers: sociaal-recreatieve reizigers, forenzen en mensen die op zakenreis gaan. De hyperloop kan (een deel van) de vraag voor concurrenten, zoals de luchtvaart, hogesnehleidslijnen en auto's, overnemen door snellere reistijden, verbeterd comfort en potentieel lagere ticketprijzen. Omzet wordt gegenereerd door het verkopen van kaartjes en concessies op hyperloopstations. Omzet kan ook gegeneerd worden door het gebruik van de hyperloopinfrastructuur voor andere doeleinden naast hyperloop zelf, zoals het verwerken van ondergrondse bekabeling en riool in het buizennetwerk (als deze onder de grond geplaatst is). De marktpositie van hyperloop wanneer deze vergeleken wordt met andere vormen van transport, zoals de auto, de bus, de trein, hogesnelheidslijnen en de luchtvaart, is sterk op het gebied van korte reistijden, comfort en tijdigheid op langere nationale en internationale afstanden.

Barrières in Hyperloopontwikkeling en Implementatie

Als transportconcept zijn er nog vele barrières die de hyperloop moet overkomen voordat deze geïmplementeerd kan worden. De eerste is standaardisatie. Er zijn verchillende technieken die gebruikt kunnen worden om hyperlooppods te laten zweven en voort te stuwen. Echter vereisen sommige zweeftechnieken het gebruik van bepaalde voorstuwingstechnieken, waardoor niet iedere combinatie mogelijk is. Als verschillende hyperloopbedrijven andere technieken gebruiken op hun pods en in de baan, kunnen pods van het ene bedrijf potentieel niet over de baan van een ander. Het gebrek aan een coherent hyperloopnetwerk kan daardoor leiden tot inefficiëntie in diens functioneren als transportmiddel. Internationale standaarden moeten daarom gezet worden om dit te voorkomen. Voor een Europees hyperloopnetwerk is het onvermijdelijk dat hyperloopbuizen grenzen oversteken, zowel internationaal als nationaal. Voor een succesvol netwerk is het belangrijk dat alle landen en regio's waar de buizen doorheen lopen het eens zijn op het gebied van wetgeving, ruimtelijke ordening en politiek. Tenslotte, een hyperloopnetwerk zal erg duur zijn door de hoge kapitale kosten. Dit vereist een enorme investering, waarschijnlijk van meerdere partijen, zowel privaat als publiek.

Externe Effecten en Sociale Verdiensten

Een hyperloopnetwerk brengt ook externe effecten en sociale verdiensten met zich mee. De snelle reistijden die de hyperloop biedt, kan een effect hebben op de werkgelegenheid en huizenmarkt in en rondom steden met een hyperloopstation. De hyperloop kan ook een effect hebben op verkeersopstoppingen als automobilisten gebruik gaan maken van de hyperloop. Doordat pods zich bevinden in een afgesloten buizennetwerk is de kans botsingen met externe objecten vrij klein. Echter, door de hoge snelheden waarmee pods zich voortbewegen kunnen botsingen met andere pods en heftige schade aan de buizen sneller fataal zijn voor inzittenden. Het is daarom van belang dat strenge veiligheidsstandaarden worden geformuleerd, zodat hyperloop op zijn minst het veiligheidsniveau heeft van luchtvaart. Een hyperloopnetwerk zal ook een effect hebben op het milieu. Een hyperloopnetwerk functioneert volledig op elektriciteit, dus als deze elektricietisconsumptie voorzien wordt door duurzame bronnen, stoot het netwerk geen schadelijke gassen of broeikasgassen uit tijdens operatie. Echter, het fabriceren en bouwen van een buizennetwerk van honderden kilometers lang zal wel veel broeikasgassen uitstoten. Dit moet meegenomen worden wanneer de hyperloop's impact op het klimaat vastgesteld wordt. Een hyperloopnetwerk zal ook ruimtelijke effect met zich meebrengen. De buizen kunnen onder de grond gelegd worden, waardoor de kapitale kosten zullen groeien door de aanleg van tunnels, maar zo neemt de hyperloop geen grond in beslag en zal er geen horizonvervuiling zijn. Door de buizen boven de grond te leggen zullen de kapitale kosten dalen, maar de impact op leefomgeving en horizonvervuiling zullen toenemen.

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List of Abbreviations

SCBA	social cost benefit analysis
HSR	high speed rail
MagLev	magnetic levitation
BR	blockage ratio
LIM	linear induction motor
LSM	linear synchronous motor
EU	European Union
TEN-T	Trans-European Transport Network
ERA	European Union Agency for Railways
PPP	public-private partnership
RFP	request for proposal
ROI	return of investment
R&D	Research and Development
NIMBY	not in my backyard
LCA	life cycle analysis

Preface

This report is a final product of research written by the Full-Scale Engineers of Delft Hyperloop VI. Delft Hyperloop VI is a team comprised of 38 students from the Delft University of Technology who spent almost a year, either full-time or part-time, working towards the realization of the hyperloop concept. In previous years, Delft Hyperloop competed in the SpaceX Hyperloop Pod Competition by fully designing, building, and testing hyperloop prototypes, called pods. Besides this, the Scalability Department of Delft Hyperloop takes on design and research challenges to bridge the gap between the hyperloop concept and its realization. The Scalability Department consists out of a Design Team and a Full-Scale Team. The first creates thought-out designs of the hyperloop infrastructure and service, the latter conducts research into the technologies, infrastructure, socio-economic effects and necessary steps for the operation of the hyperloop system.

This year, Delft Hyperloop VI will compete in the second edition of the European Hyperloop Week from the 18th until the 24th of July 2022. In this competition, the Scalability Department will compete in the two Full-Scale Awards, the Technical Aspects of Hyperloop systems Award and the Socioeconomic Aspects of Hyperloop Development Award. This document serves as the submission for the Socioeconomic Aspects of Hyperloop Development Award. Submissions to this award must focus on the non-technical aspects of hyperloop, such as cost estimates, demand modeling, predictions of socio-economic effects and route planning.

By sharing our knowledge to the hyperloop community and the rest of the world, the Scalability Department of Delft Hyperloop strives to contribute to the acceleration of the implementation of the hyperloop as a new mode of transportation.

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Chapter 1

Introduction

In 2015, the Paris agreement with the goal to limit global warming well below 2 degrees Celsius was accepted by 196 parties. To reach this goal, the Paris agreement invites countries to come up with a long term plan to reduce greenhouse gas emissions (UNFCCC, n.d.). The largest emitter of greenhouse gasses after the production of energy and heat is the transport sector, with 16.2% of all emissions (Ritchie et al., 2020). To reach the goals of the Paris agreement, drastic changes are necessary.

Two years ago, the world was hit by a global pandemic. The lock-downs that accompanied the rapid spread of Covid-19, caused a major dip in global emission. Particularly, the aviation sector showed its contribution to greenhouse gasses, as restrictions caused the emissions coming from this sector to fall 48% compared to 2019 (Tollefson, 2021a; Burgueno Salas, 2022). The overall public transport sector saw a 40 – 70% decline in passengers, having a very positive effect on the greenhouse gas emissions. Even though people were made aware of what a change in behavior could mean for the environment, the changes will not be permanent. Now already, a global rebound in emissions can be measured and researchers expect that global emissions will be back to pre-pandemic levels within a year (Tollefson, 2021b). Though it is a good thing that economies were able to quickly recover from the disaster, carbon emission levels are now recovering even faster than scientists expected (Tollefson, 2021b). It is becoming more and more clear to governments and citizens that going back to our old ways is no longer an option.

Now, public transport in Europe already sees rises again (Lozzi et al., 2022) and the recovery of air passenger transport is heavily fueled by leisure trips (Bouwer et al., 2021). Generally, the wealth of people grows and this is reflected in their demand for travel. In the next 30 years the demand for transport is expected to triple (Kloth, 2019). And while trains are generally known to be the more eco-friendly option, most people still choose to take the faster, sometimes cheaper airplane (Glusac, 2019).

The world is in need of a more sustainable way of fast transportation. In order for countries to effectively cut their CO_2 emissions, changes need to be made in the way people travel medium to long distances. Current options, such as rail transport and aircraft are either very polluting or not fast enough.

The hyperloop is a concept that could prove to be a solution. The technology is evolving rapidly and many big parties are involved (Bright RTL nieuws, 2022; SpoorPro, 2021; Innovation Origins, 2021; Railway Technology, 2022). It provides the operational speeds of aircraft with an energy consumption that is assumed to be less than that of high-speed rail (HSR; Taylor et al., 2016; Dabrowska et al., 2021). The hyperloop is also assumed to run on electrical energy, which can be provided through sustainable energy sources, thus minimizing the emissions of greenhouse and toxic gasses. In short, the hyperloop is fast and sustainable, therefore combining the best of both worlds. The hyperloop concept uses a network of vacuum tubes through which capsules (pods) travel. These pods levitate and move through the use of magnets. These technologies eliminate most air resistance and friction forces, allowing the pods to travel at speeds of 1000+ km/h with a very low energy consumption. Passengers of the hyperloop are therefore able to travel, for example, between Amsterdam and Paris in just 30 minutes.

1.1 Problem Description

There are still a lot of challenges that the hyperloop concept needs to overcome before implementation. A large share of these challenges come into play in the investment and initial decision-making process. The many stakeholders that are involved in this phase are confronted with a large range of questions, of which the choice of where to build a hyperloop corridor is a prominent one. Which two cities would benefit most from a connection with a hyperloop and why? In order to make investing in hyperloop infrastructure attractive and profitable, it is of essence to have a clear idea of what a successful corridor would be and what factors have to be taken into account.

Currently, in this stage of hyperloop development, an overview with structured and transparent information that is necessary for deciding on a feasible corridor, is largely absent. In literature, unambiguous overviews of important assumptions on hyperloop infrastructure, effects induced by placing a hyperloop corridor between two cities and which stakeholders are involved in what parts of hyperloop construction, are still missing. Having a clear groundwork in this kind of information can significantly help the efficient realization of hyperloop infrastructure in the long term.

1.2 Aim of the Report

In order to develop a hyperloop corridor between two cities, there needs to be a commissioning party to initiate the project, and an investor is needed to fund the implementation. Before these parties decide to initiate and finance the organization of a large project such as the realization of a hyperloop corridor, they will need to gather and process a lot of information.

The commissioning parties and investors can be split into two groups: coming from the public sector and coming from the private sector. Investors or commissioning parties in the private sector can be found as private companies or wealthy individuals; commissioning parties or investors in the public sector are commonly governments, both local and national, but also larger, international institutes, such as the European Commission. For these private and public parties, it is essential to be aware of all of the social and economic effects that are to be expected when making a decision to build a large infrastructure such as a hyperloop corridor. For the decision-making process to be efficient and transparent, it is important that the tools used are based on a set of complete and cohesive assumptions. Moreover, all the effects and benefits should be known and incorporated in deciding on the hyperloop corridor. For a new infrastructure network such as the hyperloop, it can be rather time consuming and hard to gather this information, since no clear overviews and data collections exist yet.

Delft Hyperloop strives to make the reasoning behind the decision-making process as clear and transparent as possible. This report provides a basis of knowledge about the hyperloop, participation strategies for stakeholders, business case details and external effects that will be helpful to private and public parties when taking on the task of deciding where to implement a hyperloop corridor. In that light, a clear overview is proposed that can support decision-makers and lay foundations for their work. The overview of principles of the hyperloop system and infrastructure, presented in this report, provides information that is collected from a broad variety of trusted sources, or deduced from sources with clear and transparent calculations. The collected information in this report is kept to a conceptual level. The aim is then to make this overview applicable to any two cities in Europe that would be connected with a hyperloop corridor. This will work towards the standardization and clarification of the decision-making process of developing hyperloop infrastructure. The information provided can be used in models, social cost-benefit analyses (SCBAs) and other decision-making tools, thereby saving possible investors the step of gathering relevant information and launching them immediately to comparing and deciding.

1.3 Method

This report provides a basis for decision-making tools that can be used in the process of developing and implementing a hyperloop corridor. To achieve this, a literature review is performed on reports about the hyperloop and other large infrastructure projects. Additional information about strategies and effects of the implementation of the hyperloop resulted from brainstorms and workshops with experts from TNO, the TU Delft faculty of Technology, Policy and Management, Berenschot, Decisio and the Dutch Ministry of Infrastructure and Water Management and Ministry of Economic Affairs and Climate Policy. The overview of decision-making information that is presented in this report is structured as follows.

In Chapter 2, an overview of principles related to the operations and characteristics of the hyperloop is created. This guide to the basics of the hyperloop is based on known literature or deducted from it in a transparent way.

Chapter 3 gives an analysis of the stakeholders that would be involved with the development and implementation of a hyperloop corridor in Europe. Followed by the analysis, different participation strategies are given, as well as the different phases of the implementation of the new infrastructure of the hyperloop. The analysis, strategies and phases are based on information coming from existing frameworks and the analysis of stakeholder strategies from other large infrastructure projects, such as high speed rail lines. Additional insights into the hyperloop stakeholders, the different participation structures, and the phases of infrastructure project were established as a result of brainstorms with experts from both the public and private sector.

In Chapter 4 the different aspects of the hyperloop business case are discussed. The sides of a possible business case are reviewed on a conceptual level. Information in this chapter is based on estimations from external sources, brainstorms with experts and literature about comparable infrastructure projects.

In Chapter 5 the barriers that the implementation of the hyperloop hinder are explored and discussed. Expected barriers are derived from literature and are the result of brainstorms with experts.

In Chapter 6 the social and economic effects that come with the construction of a hyperloop corridor are identified and described in detail. To do this, frameworks and examples from large infrastructure projects such as HSR or high way connections are analyzed and extrapolated to the hyperloop. Expectations of the possible effects are found with thanks to discussions and workshops with experts.

Lastly, in Chapter 8 the next steps towards the implementation of the hyperloop are discussed. Here, recommendations are given for actions that can be taken in order to create more clarity and progress in the development of a future, commercial hyperloop.

Chapter 2

Principles of the Hyperloop System

The publication of Elon Musk's Hyperloop Alpha paper (Musk, 2013) has initiated a cascade of research, innovations and numerous more publications on the hyperloop. Because of the rapid developments in this community and the many organizations that do research and innovate their technology, it can be hard to keep up with recent developments and have a clear view of the exact workings of the hyperloop. For decision makers, however, who would evaluate the hyperloop as a new mode of transportation and are weighing all of the pros and cons of implementing a whole new infrastructure, it is very important to have a clear idea of the system they are talking about. Therefore it is of great value for decision-making to have a basis description of the system that is talked about and to have unity in assumptions.

In this chapter, the whole hyperloop system is explained and analyzed. It is explained how the hyperloop works, what it will look like when integrated into our future lives, and what the hyperloop could add to our current transportation sector. After an introduction of the global working of the hyperloop concept, a detailed explanation is given of the design, with all its dimensions, of the hyperloop pod as it is viewed by Delft Hyperloop VI. Next, the operations of the hyperloop are analyzed. All necessary assumptions are collected from other sources and inventorized into a clear, substantiated overview of the typical operations of the hyperloop system. This description is followed by assumptions and calculations regarding the energy consumption of the hyperloop and the expected costs of implementation and maintenance. The initial collection of assumptions from other sources and the conclusion drawn from these by Delft Hyperloop VI can be found in Appendix A.

2.1 What is the Hyperloop?

The hyperloop is a new mode of transportation next to boats, cars, trains and planes, that fits somewhere between the latter two. By taking away all rolling resistance and most air resistance of a train-like vehicle, the hyperloop can reach speeds of 1000 km/h with an energy consumption that is comparable to that of high speed rail (HSR). Because of the high speeds, hyperloop can connect distant cities in different countries and transport large volumes of passengers and cargo.

How does it work?

With the hyperloop, the rolling resistance of the vehicle is taken away by removing all physical contact with the track. The vehicle, called a pod, levitates under the track via an electromagnetic suspension system. Magnetic fields combat the force of gravity to let the pod levitate steadily at a set distance from the track. The pod moves through tubes from which almost all of the air is removed by vacuum pumps. The low pressure environment in the tubes drastically reduces the air resistance the pod will experience while traveling. Lastly, the pod is also propelled by magnetic forces. A linear motor is a linearized motor configuration that has a part in the track and a part mounted on the pod. Permanent magnets are attracted and repelled by electromagnets making the pod accelerate, decelerate or move at a constant speed.

The hyperloop system is fully electric, working with electromagnetic fields for levitation and propulsion, and using electrical vacuum pumps. The addition of green electricity sources and a climate neutral construction process of the infrastructure would make the hyperloop a highly sustainable and environmentally friendly mode of transport.

Why do we need a hyperloop?

In the past 30 years the demand for transportation has grown both in distances and volume, and it is expected to grow even more in the coming 30 years. At the same time, climate change is becoming a more and more urgent issue to solve

Figure 2.1.1: Image of Delft Hyperloop's vision of the hyperloop in a Dutch landscape.

if we want to keep living on this Earth with this many people. With the transportation sector being one of the largest energy consumers and responsible for at least a quarter of all CO_2 emissions, the demand for this sector to become more sustainable is greater than ever (Dabrowska et al., 2021). There is a need for a more efficient, more sustainable mode of transportation that has a large capacity and meets the demands for comfort of modern travelers. The hyperloop could fill this gap.

With its high efficiency and high speed, the hyperloop combines the best features of traveling by train and by plane. However, it will not replace these modes of transport. As Hardt, the Dutch hyperloop company, accurately words it: "Hyperloop is an additional modality rather than an alternative one, however it is likely to change the use of current modalities. Hyperloop would connect cities that lie between 50 – 3000 km apart, making short-haul flight substitution possible and offering a faster, more energy efficient alternative to high speed trains, and simultaneously freeing up slots on congested airports" (Hardt, 2020).

A European Hyperloop Network

With the distances that the hyperloop covers comfortably, a hyperloop network can be seen as a transportation network that covers one continent. As the hyperloop is intended as an improved addition to transport, aimed to serve modern travelers, a network could be best envisioned in North-America, Europe or China. In this report, all research is focused on a European hyperloop network. This is because Delft Hyperloop is a Dutch student team, and this report is a deliverable for the European Hyperloop Week, a conference and competition between hyperloop student teams, that is based in Europe. Therefore, with an eye on relevance and accessibility of the right sources, the focus of this report is a European hyperloop network.

The next sections of this chapter dive deeper into the design and working of the hyperloop system. These sections give an overview of all that is known about the hyperloop and give assumptions that are needed to make decisions about the integration of this new transportation mode into society.

2.2 The passenger pod

To analyze the design of the hyperloop system and all assumptions around it, the starting point is the moving vehicle that carries passengers or possibly cargo from origin to destination, the so-called pod. For this report, reasoning is based on a passenger pod, since this will gives more size restrictions to base the assumptions on. Also, a pod and tube that are based around the transport of people can be adapted to transport cargo by rearranging the interior of the pod and adapting cargo units to fill it up. A pod that is based on the transport of cargo however, is harder to adapt to carry people. Cargo departments are not always appropriately sized for the dimensions of humans. All assumptions in this chapter are, therefore, based on the passenger pod.

Expectations of the Demand of the Hyperloop

The hyperloop is proposed as a mode of transport that is able to partly replace current transport on short to medium distances. These distances are currently covered by short haul flights, HSR connections or in some cases even only a high way connection. The hyperloop, with its high speeds and low energy consumption promises to be a fast and efficient replacement for these tracks. There have been some estimations on the demand for fast transport on these corridors (Musk, 2013: Delft Hyperloop III, 2019). However, making a good estimation of the demand is extremely hard as it is yet unknown how many passengers the hyperloop can take from the HSR and continental flights. It might also be possible that the arrival of the hyperloop creates new passenger flows. A more detailed analysis of the expected demand will be presented in Section 4.2. In accordance with the predictions made by Elon Musk in the Hyperloop Alpha paper, it will be assumed in this report that pods will travel through the tubes every 120 s at normal hours or at a maximum frequency of 1 pod every 30 s for rush hours (Musk, 2013). Based on calculations made by Delft Hyperloop III, this report assumes a hyperloop pod that seats around 50 people (Delft Hyperloop III, 2019). This means that the regular capacity of one hyperloop tube would be 1500 passengers per hour and 6000 passengers per hour for rush hours.

In passenger experience, the hyperloop is expected to be something in between a train and a plane. Hyperloop stations will resemble those of trains, since there is no need for any runways. This means that stations can be built close to or even in city centers, if space allows it. Together with fast check-in procedures, the hyperloop will provide the same ease of travel as a train does. However, because of its large speeds and generally longer travel distances in comparison with trains, the hyperloop will work with allocated seats, bookings and mandatory seat belts. Following this comparison, the boarding time for the hyperloop will also be somewhere between that of trains and planes. At a stopover, a train usually lets passengers embark and disembark for time of 30 to 120 seconds. A plane however, has a boarding time of at least 15 minutes. For the hyperloop it is assumed that the boarding time of a pod is between 5 and 15 minutes, dependent on the capacity of the station (how many pods can be standing still and boarding passengers at a time).

The Size of the Pod

A hyperloop pod will in appearance closely resemble a single train carriage or airplane cabin that has seating for 50 passengers. Based on aircraft fuselage proportions, the passengers will sit in rows of 3 seats (Delft Hyperloop III, 2019). The pod will have two seats on one side of a central aisle and one on the other. So a pod with 16 rows of 3 seats will fit 48 passengers. To enter the pod, there will be four doors, two on each side. These doors will connect to bridge door airlocks in the station. This allows passengers to move safely from pod to station without the pod having to leave the vacuum tube. The advantage of using bridge door airlock instead of, for example, airlock chambers that allow the pod to leave the tube and move freely in the station, is that the first method only requires a small volume to be pressurized and depressurized at every stop. This will significantly shorten the time that a hyperloop pod needs to wait in a station and that will contribute to the fast transport image hyperloop stands for (Delft Hyperloop V, 2021a).

With the 16 rows of chairs, two sets of doors, a bathroom and two aerodynamic cones on the front and back of the pod that accommodate the batteries, oxygen tanks and other technical parts, the total length of the pod will be $l_{\text{pod}} = 30$ m.

Based on the antropometric data of an average Dutch person in sitting position, the mean popliteal height (seat height) is 456 mm. The mean hip breadth in sitting position is 406 mm, and the mean total height of a sitting person is 1349 mm, (Huysmans and Molenbroek, 2000).

Using this data of human proportions and the sizing of first class HSR chair (from for example Jung et al., 1998), a hyperloop seat will have a seat height of 45 cm, and width of 47 cm, the height of the back rest will be 90 cm. The armrests of the single seat will have a width of 9 cm, making the total width of a single chair 65 cm. For the double seat the middle armrest will have a width of 13 cm, making the total width of a double chair 125 cm. The width of the aisle will be 50 cm, and the height will be 200 cm.

A cross section of the pod with all sizes and dimensions is given in Figure 2.2.1. With the help of this figure, the frontal area of the pod is calculated to be $A_{\text{fp}} = 6.678$ m^2.

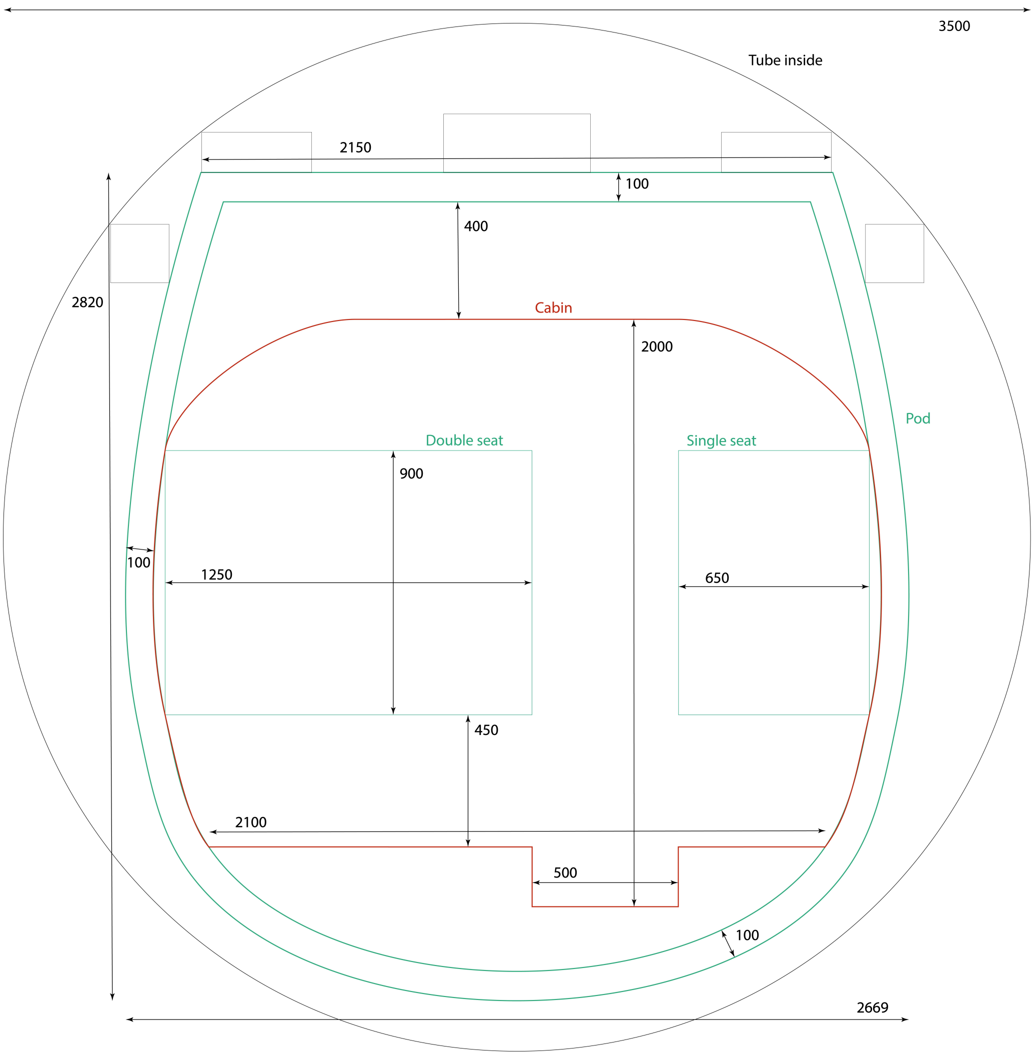

Figure 2.2.1: Schematic drawing of the cross section of the pod in the tube. All indicated sizes are given in millimeters. Under the floor of the cabin section there is room for passenger related technical parts, such as inner pressure control devices, oxygen tanks and supporting systems for the lighting and information screens. The space overhead is meant to store parts of the propulsion and suspension system of the pod, including a magnetic shield to ensure safety of the passengers from the strong magnetic fields that are used to propel and levitate the pod.

The total weight of the pod can only be calculated when the weights of all subsystems and components are known, moreover, also the weight of the passengers and their luggage or the weight of the cargo that is being transported in the hyperloop pod. For this report, the mass of the pod is based on the initial estimation done by Musk, which was 15 tonnes (Musk, 2013), and the mass of a MagLev train, which uses comparable technical components as the hyperloop and comes in at a mass of 25 to 30 tonnes (Zhai et al., 2019). Since the hyperloop uses a different, lighter levitation technique compared to the MagLev, the mass of the pod is assumed to be $m_{\text{pod}} = 20000$ kg. The dimensions of the hyperloop pod that have been deduced in this section are summarized in Table 2.2.1.

Table 2.2.1: Dimensions of the hyperloop pod.

Name	Quantity	Value	Unit
Passengers per pod	$n_{\text{passenger}}$	48	–
Pod length	l_{pod}	30	m
Pod height	h_{pod}	2.82	m
Pod width	w_{pod}	2.67	m
Frontal area	A_{fp}	6.68	m^2
Pod weight	m_{pod}	$20{\cdot}10^3$	kg

(a) Passenger seat inside the hyperloop pod as designed by Delft Hyperloop V. The seat is provided with a screen for information about the itinerary, and contact with the hyperloop operator, when necessary. On the side of the chair an emergency kit is located, to be used in case of a pressure drop inside the cabin.

(b) Passenger seats inside the hyperloop pod as designed by Delft Hyperloop IV. The ceiling of the passenger cabin features lighting and screens to simulate surroundings and visual movement. The sides feature screens with information about the itinerary and the possibility to contact the external hyperloop operator.

Figure 2.2.2: Visuals of the inside of the hyperloop pod as designed by Delft Hyperloop.

Passenger Experience

A hyperloop pod is comparable with a single coach of a train, but there are a few differences. The first is of course that the pod moves through tubes that are brought to a pressure of a thousandth of the atmospheric pressure. Because of this large pressure difference in and outside of the pod, passengers will sit in a pressurized compartment where air is circulated and oxygen levels are constantly monitored and controlled. This is very similar to the passenger area of an airplane. The hyperloop is an autonomous vehicle, meaning that the pods do not have a driver. Passengers will not take much notice of this, since every seating will be provided with screens that show information about the journey. This will give passengers a feeling of overview, safety and control. In addition to this, the removal of a driver in the pod also takes away all possibility of human errors on the vehicle side, thereby making the hyperloop even safer.

As the pod moves through tubes that are made of generally thick, opaque material, it is not possible to look outside during the trip. The pod will therefore also not be supplied with windows. Even if it would be possible to look outside from a moving hyperloop, this would not be preferable. At the cruising speed of the pod, it would look as if the surroundings were passing by at 1000 km/h. At this speed, buildings and trees would be reduced to a blur to the human eye, causing nausea and motion sickness.

However, to reduce the feeling of being in a closed off space when traveling in the hyperloop pod, the ceiling of the pod will feature bright lights and screens with passing landscapes. This will give passengers a feeling of open space and movement at a more comfortable speed. The bright space and artificial passing of the surroundings will also combat the feeling of motion sickness and make traveling in a hyperloop pod a more natural experience. In Figure 2.2.2 two different designs of the inside of the hyperloop passenger pod are shown.

Passenger Safety

The hyperloop is propelled and levitated with the use of strong magnetic fields. Since the pod hangs from the track, these magnetic fields are located above the passengers' heads. Smart orientation away from the passenger of the permanent magnets that are mounted on the top of the pod and a thick metal shielding in the ceiling will however protect the passengers from all of the magnetic field. Even persons that use magnetic field sensitive devices for cardiac arrhythmia can safely use the hyperloop. As stated by Hardt on their website: "a person holding a fridge magnet will experience multiple orders of magnitude stronger magnetic fields than in the Hyperloop" (Hardt, 2020).

Since the pods move through vacuum, leaving the vehicle in case of an emergency will work differently from, for example, a train. In the very unlikely event of an emergency due to technical failure, the pod will automatically come to a halt with a fast but safe deceleration rate of 1 G. If possible, the pod will move to a safe haven compartment that has exits in the tube that will allow passengers to leave the infrastructure in the same way passengers would disembark in a station. If it is not possible to reach a safe haven, the pod will stop inside the tube. This compartment of the tube will be sealed off and brought back to atmospheric pressure. Passengers can then leave the pod into the pressurized tube and walk to the nearest exit point. Via the inter-pod communication links, other pods will be notified of the stranded vehicle and, if possible, automatically find a detour around the pod via high speed lane switching.

2.3 An Infrastructure of Tubes

Probably the most characteristic part of the hyperloop system are the depressurized tubes that define the general infrastructure. The size and properties of the tubes are very important for the companies that will build them when the hyperloop infrastructure is implemented.

Dimensions of the tube

The hyperloop pods move through tubes that maintain a low pressure environment. The ideal diameter of the tubes depends on multiple factors. First of all, the pods should be able to move through the tubes, imposing a minimal diameter on the tubes. But because of the circular shape of the tubes, increasing the diameter of the tubes will increase the outer area of the tubes with a factor of π (≈ 3.14), and therefore the building materials and costs of them. So, it will be financially beneficial to keep the tubes as narrow as physically possible. Small tube diameters that have been proposed are 3 m (Arup et al., 2017; AECOM, 2020) and 2.5 m (Dabrowska et al., 2021), although the latter is only proposed for the purpose of transporting cargo.

Alternative pod size

For a tube diameter of 3 meters, immediately the problem is identified that the pod, with the layout and sizes that were proposed in the previous section, simply does not fit. What would fit in the 3 meter tube is, for example, a cylindrical pod with a diameter of 2.2 m (Arup et al., 2017). Considering that you need a level floor and room to store necessary technical parts of the pod, it will be impossible to have an aisle in this pod, where people could stand upright. The smaller pod size would probably have rows of two seats abreast with no aisle in between. With the absence of an aisle, all passengers will need their own door to embark and disembark the pod. If the hyperloop system will still work with airlock doors that connect the pod inside with the station, there will need to be 48 airlock doors at every platform of every hyperloop station. Installing that many airlock doors will be hard to finance. In that case the option of having an airlock chamber that connects the low pressure tube to the station might have to be reconsidered. However, as has been found by Delft Hyperloop V, 2021a, using an airlock chamber takes a lot of time for a pod to enter and leave a station. This is not compatible with the fast transport image that the hyperloop is supposed to have.

Because of this, the pod sizes and configuration that are given in Figure 2.2.1 continue to be used in this report, and also a tube diameter that fits nicely around it. The inner diameter of the tube is assumed to be $d_{\text{tube}} = 3.5$ m. An outline of this inner tube diameter is also drawn in Figure 2.2.1.

With the frontal surface of the pod, the blockage ratio (BR) can be calculated. This is the ratio between the frontal surface of the pod and the cross section of the tube. This gives $BR = 0.694$. The blockage ratio is an important number for calculations on the aerodynamics of the pod in the tube.

Tube pressure

The aerodynamic drag of the pods scales also with the pressure in the tube. The lower the pressure, the less drag you will experience. However by decreasing the pressure in the tube, the energy consumption of the vacuum pumps used to pump down the space and maintain the operational pressure, will increase. On the other hand, for higher pressures the energy required for the electromagnetic propulsion system will be larger. It was calculated by Decker et al., 2017 that the optimal pressure in terms of energy costs of the whole system, lies at 200 Pa. However, this study was based on a comparably small pod diameter and large tube diameter, i.e. much room for air to flow past the moving pod. For larger frontal area of the pod and smaller tube cross section, a lower pressure will become more and more important, in order to not choke the air flow at high operation speeds. For this report, the pressure in the tubes will be assumed to be $p_{\text{tube}} = 100$ Pa (Musk, 2013; Opgenoord and Caplan, 2018; Sane, 2020).

Infrastructure

Hyperloop tubes can be built in 3 different vertical alignments: underground, on the ground and above ground on pillars. Which vertical alignment works best, depends heavily on on the area that the hyperloop is crossing. In nature reserves, it will be beneficial to put tubes underground, as to not disturb the landscape. In urban areas it might be beneficial to also build tubes underground to not interfere with existing infrastructure, or for that same reason above ground, if the underground space is already occupied by existing infrastructure. On the other hand, in rural areas, above ground on pillars might be the best option as it saves on tunneling costs and limits the disturbance of land. A complete assessment of the vertical alignment options has been made by Delft Hyperloop V (Delft Hyperloop V, 2021b).

Based on the length of the pod and common span distances for elevated tube or bridge structures, the pillar spacing of the parts of the tube that rests on pillars, is assumed to be $s_{\text{pillar}} = 30$ m. The height of these pillars is based on the average height of viaducts in the Netherlands and will be assumed to be $h_{\text{pillar}} = 5$ m. The dimensions of the hyperloop tube that have been deduced in this section are summarized in Table 2.3.1.

Table 2.3.1: Dimensions of the hyperloop tube.

Name	Quantity	Value	Unit
Tube diameter	d_{tube}	3.5	m
Blockage ratio	BR	0.69	-
Tube pressure	p_{tube}	100	Pa
Pillar spacing	s_{pillar}	30	m
Pillar height	h_{pillar}	5	m

Safety in Depressurized Tubes

Safety is a very important aspect of any mode of transportation. Since hyperloop is a new concept, safety standards and emergency protocols are still being developed. Delft Hyperloop has done extensive research towards designing a safety framework for hyperloop (Delft Hyperloop IV, 2020).

One of the biggest safety challenges that the hyperloop faces is the vacuum tube environment. If a pod malfunctions, passengers cannot simply walk out of the pod and flee to a safe space. A solution to this is the 'safe haven' concept. Much like emergency lanes along highways, safe havens are small lengths of tube that run alongside the main tube which include emergency exits. In case of emergency, pods can move into a safe haven, which then (partially) pressurizes to enable passengers to leave the tube.

Another big part of the safety of the system is the sturdiness of the tube. A large network of tubes is a revolutionary technique for the passenger transportation sector. However, there already exist very large tube networks for the transportation of gas or industrial liquids, such as oil pipes. Therefore, there is a lot of knowledge about how to build these kind of structures safely and robust. Thermal expansion is for example compensated by expansions joints that can be compressed and stretched. The round structure of the tube is on itself also one of the strongest structures possible and tube construction can be built to even resist earthquakes. In case of an earthquake, the pod will come to a halt and wait until the shocks are over, while still monitoring the stability of the pod and correcting its position when necessary. After the event, the hyperloop will move to the nearest station (Hardt, 2020).

Even the huge pressure difference between the inside and outside of the tube is not a new phenomenon. Gas and oil pipes that lie for example underground or on the bottom of the sea, also experience a large pressure from outside. Therefore there has already been lots of research into the prevention of buckling and implosion of these kind of tubes.

2.4 Operations of the Hyperloop System

Just as important as the physical parts of the hyperloop for the decision-making process around implementing the infrastructure, are information and assumptions related to the general operations of the hyperloop system. These will be analyzed in this section.

Speed characteristics

As has been established, the average cruising speed of the hyperloop shall be assumed to be $v_{\text{cruise}} = 1000$ km/h. To get to this cruising speed from stationary position at, for example, a station, the hyperloop will accelerate using the linear motor. Although the linear motor can achieve very high acceleration rates, the maximum linear acceleration must be bounded by the level of comfort for the passengers. This means that the acceleration will require a large distance and passengers will experience a relative slow acceleration, comparable with the acceleration rates of a high speed train. The maximum linear acceleration should be 0.1 G (AECOM, 2020), which is still much lower than the acceleration felt in a departing airplane.

In terms of safety for the passengers, the emergency brake deceleration of the pod should also be regulated. The maximum deceleration should not be so hard that passengers might hurt themselves, but should be fast enough to ensure a quick and safe total stop from cruising speed. Assuming that passengers wear a seat belt during the trip, the emergency brake deceleration is decided to be $a_{\text{emergency}} = 1$ G (AECOM, 2020). With this deceleration speed, a pod will be able to make a full stop from going 1000 km/h in 28 s. This means that the rush hour pod frequency of one pod per 30 s, that was given in Section 2.2, is the absolute maximum for safety reasons, in order to not collide with the preceding pod.

With the cruising speed and the maximum acceleration of $a_{\text{pod}} = 0.1$ G, it can easily be calculated after how much distance the hyperloop reaches its cruising speed. The distance passed before reaching cruising speed is given by $s_{\text{cs}} = 40$ km.

Operational distances

Since the hyperloop hardly uses any energy when traveling at a constant speed, it is more efficient to travel distances that are longer than the path it takes to get to speed and to slow down. Therefore the minimum length of a hyperloop corridor, a piece of uninterrupted hyperloop track, is set to be $l_{\text{min,corridor}} = 100$ km. At this distance, 20% of the journey can be traveled at cruising speed.

In terms of efficiency, the maximum length of a hyperloop corridor can also be identified. This is assumed to be $l_{\text{max,corridor}} = 1500$ km. After a distance of around 1500 km the energy consumption per km per passenger of an airplane starts to drop rapidly to a level at which they can compete with a hyperloop on an economic level, in speed and eventually in energy consumption (Musk, 2013; Federici et al., 2009). Here it is also important to note again that the hyperloop infrastructure is one that needs to be constructed entirely before a corridor may be used. Therefore, a corridor that is longer than 1500 km will likely not find enough funding (Delas et al., 2019).

Turns and switches

To ensure a comfortable trip in the hyperloop pod at speeds of $v_{\text{cruise}} = 1000$ km/h, the maximal lateral acceleration that a passenger can experience in a turn will be restricted. The maximal lateral acceleration is set to be $a_{\text{max,lateral}} = 0.4$ G, (Santangelo, 2018; AECOM, 2020; Bae et al., 2020).

With the maximal lateral acceleration set, the smallest radius of a turn in the hyperloop track can be calculated. With the smallest radius that a turn can have, it is also possible to calculate the length of a high speed switch. This is a switch that can be passed at the full cruising speed of a hyperloop. The full calculations of the smallest radius of a turn and the minimal length of a switch can be found in Appendix B. Here, just the results are given: $R_{\text{turn}} = 19.7$ km, $l_{\text{switch}} = 400$ m.

Important to note here however, is that the radius of a turn may actually be smaller than calculated, even though the hyperloop is going at full cruising speed. This is because the hyperloop is able to bank due to the hanging suspension system. Because the hyperloop levitates towards a track that is located at the top, the pod can bank safely at high angles, without losing stability (Hardt, 2020). Banking is also a more comfortable way of taking a corner in terms of passenger experience. By tilting the vehicle, part of the lateral acceleration will be pointed towards the bottom of the pod, thereby reducing the feeling of taking a sharp turn. The general assumptions on the operations of the hyperloop are summarized in Table 2.4.1.

Table 2.4.1: List of assumptions on the hyperloop system made by Delft Hyperloop VI.

Name	Quantity	Value	Unit
Cruising speed	v_{cruise}	1000	km/h
Maximum linear acceleration	a_{pod}	0.1	G
Maximum lateral acceleration	$a_{\text{max,lateral}}$	0.4	G
Emergency brake deceleration	$a_{\text{emergency}}$	1.0	G
Distance to full speed/stopping distance	s_{cs}	40	km
Minimum length of corridor	$l_{\text{min,corridor}}$	100	km
Maximum length of corridor	$l_{\text{max,corridor}}$	1500	km
Smallest radius of a turn (at full speed)	R_{turn}	19.7	km
Length of high speed switch	l_{switch}	400	m

2.5 The Energy Efficiency of the Hyperloop

The hyperloop is promising to be the most energy efficient mode of transport yet. By using magnetic levitation technology and a near-vacuum tube environment, rolling and air resistant forces respectively are minimized. This means that a hyperloop pod can accelerate and cruise with an energy and power consumption that is comparable to that of a high-speed train and much less than that of an airplane.

There are two main hyperloop subsystems that consume the most electrical energy. The first is the pod propulsion system. This system induces and sustains motion of the pod. The propulsion system can either be on the pod or in the track. The first method uses a linear induction motor (LIM), the second a linear synchronous motor (LSM). The first motor is cheaper to implement, while the second motor is more energy efficient. The investment costs using the LIM are therefore lower, but the operational costs of the LSM are lower. The second subsystem that uses a substantial amount of energy are the vacuum pumps bringing and keeping the air pressure in the tubes at a near-vacuum level.

Exact numbers on the hyperloop energy and power consumption do not exist yet, since no hyperloop system that can operate at 1000 km/h for a long enough distance has been built yet. However, there have been estimations by numerous parties. Hardt Hyperloop for example estimates that the energy consumption of their complete hyperloop system will be 38 Wh/passenger/kilometer (Dabrowska et al., 2021). The U.S. Department of Energy estimates the total daily energy consumption of three different potential hyperloop corridors in the United States, with the energy consumption ranging from 105 to 173 Wh/passenger/km (Department of Energy et al., 2021). This difference is mostly due to the fact that the Department of Energy uses a tube which is 0.5 meters wider in diameter, which results into more energy needed to keep the tube at a low pressure environment. Furthermore, their pods can only seat 30. Research by Janic et al. shows that pod energy consumption does not scale linearly with pod capacity, especially at longer journey distances (Janić, 2020). Pods with higher passenger capacity thus use less energy per passenger than pods with lower passenger capacity. The energy consumption of the hyperloop will therefore be somewhere in between those two figures.

To compare this with other modes of transportation, a high-speed train uses between 80 and 120 Wh/passenger/kilometer and an airplane during a continental flight uses between 350 and 520 Wh/passenger/kilometer (Dabrowska et al., 2021; Janić, 2020). This shows that the hyperloop concept is an order of magnitude more energy efficient than the airplane.

2.6 Costs of Hyperloop Infrastructure and Operations

The costs of hyperloop implementation are often considered as one of the biggest drawbacks of the concept. Since hyperloop infrastructure does not exist yet, a whole tube network needs to be built, bringing with it a lot of costs. As for any infrastructure project, the infrastructure has to be developed, manufactured, constructed, operated and maintained. The first three aspects can be grouped as capital costs of the hyperloop, the latter two as operational and maintenance costs.

The capital costs of the hyperloop are expected to be considerable. There have been numerous parties that have estimated the capital costs of a hyperloop system. Elon Musk was the first in his Hyperloop Alpha paper, where the capital costs of a hyperloop corridor between Los Angeles and San Francisco were assumed to be 13.3 million USD$ (11.5 million EUR€ in 2022) per kilometer (Musk, 2013). This number has grown over the years. AECOM created an overview of the capital costs estimated by multiple parties, with numbers ranging from 37.8 million to 56.4 million CAD$ (25.7 million to 38.4 million EUR€ in 2022) per kilometer (AECOM, 2020). Delft Hyperloop has estimated the capital costs to be between 12.3 million and 45.2 million EUR€ per kilometer (Delft Hyperloop V, 2021b). The reason why these numbers differ is due to all the different elements that were taken into account when making these estimations. For example, some studies do not include the costs of the hyperloop pods in the estimation, since it is not clear how many pods will operate in a certain corridor. Some studies also include station costs, others do not. One major difference is the assumption on the vertical alignment of the hyperloop tube. If the tube is assumed to run underground, tunnels have to be dug for the tube to run through, adding a considerable amount of costs.

The operational and maintenance costs are harder to assess, since no hyperloop system has been built. TNO has given estimates on the relative operational and maintenance costs, with maintenance taking op 58% of the costs, energy 18%, and personnel and ticketing 12% (Arup et al., 2017). Delft Hyperloop has assumed the maintenance costs of the hyperloop tube to be 50,000 – 150,000 EUR€/km/year for an above ground tube and 210,000 - 370,000 EUR€/km/year for an underground tube. A more detailed assessment of the costs of the hyperloop is given in Section 4.1.

Chapter 3

Stakeholder Analysis and Participation Strategy

The development of a hyperloop corridor is a large-scale project. The implementation of a hyperloop corridor between two cities is likely to have a wide range of effects on its surrounding environment and people. Moreover, the road from initiating a hyperloop corridor to actually constructing it, involves a diverse group of stakeholders with varying degrees of interest and power.

In a multidisciplinary and complex project as the development of a hyperloop corridor, it is essential for the commissioning party to have a clear overview of the present stakeholders, their form of involvement in the project, and their desired actions (Mok et al., 2015). This way, the commissioning party can easily identify and prioritize different stakeholders, accommodate their interests and maintain good relationships with them. This is beneficial for realizing the desired results of the project and for anticipating problems and potential conflicts. As the hyperloop is a radically new and extensive form of infrastructure, it yet remains largely uncertain what exact issues to expect throughout the entire developing phase. Yet, examples can be taken from similar infrastructure projects, such as HSR networks, in order to derive information on stakeholders and their degree of interest and involvement. By performing smooth stakeholder management, a contribution can be made to optimize the efficiency and aspired outcomes of the project (Bourne and Walker, 2005).

In essence, the stakeholder management that will be discussed in this report can be split up into two consecutive steps. First of all, a stakeholder analysis will be executed. In this step, the stakeholders are identified and classified into their type of participation and power in the project. The second step in stakeholder action is setting up a participation strategy. This states what actions are required from stakeholders at what phase in the project to work towards optimization of efficiency and results of the project. As the development of the hyperloop is still in a conceptual phase and involves both private and public parties, it is yet unspecified for participating parties when to undertake action and who to communicate and collaborate with. A participation strategy in hyperloop development can therefore contribute to making the process and communication around designing, financing and constructing hyperloop infrastructure more efficient and transparent.

To sum up, in this chapter stakeholders are identified and classified, followed by a proposal for a participation strategy which includes the required roles of the identified stakeholders in the development of a hyperloop corridor. Ideas in this chapter were established thanks to discussions with experts from TNO, the TU Delft faculty of Technology, Policy and Management, TBI and the Dutch Ministry of Infrastructure and Water Management and Ministry of Economic Affairs and Climate Policy.

3.1 Framework

There is a variety of frameworks present for performing a stakeholder analysis (Mok et al., 2015). The models used in the fields of HSR, conventional rail and aviation are of main interest for hyperloop infrastructure. It is assumed that these forms of transport involve a similar range of stakeholders to the hyperloop and are therefore taken as an example for the stakeholder analysis of hyperloop infrastructure.

In this report, the following framework is used for the analysis and classification of stakeholders. First of all, to identify the present stakeholders, a preliminary non-exhaustive list of stakeholders is made, based on brainstorming sessions with external experts and information from similar infrastructure projects.

After having identified the stakeholders, they can be characterized and prioritized by means of a power-interest matrix. This matrix is part of a popularly used stakeholder analysis method and provides a clear division of the stakeholders into four separate clusters, based on their degree of interest and power in the project. In this stakeholder analysis, power is understood as “the ability of stakeholders to exercise their influence to achieve desirable outcomes” (Guðlaugsson et al., 2020, p. 172). More specifically for this report, power is defined as the ability of a stakeholder to exercise their influence to achieve desirable outcomes in the development of a hyperloop corridor. Secondly, in this stakeholder analysis, the term interest means “the stakeholders’ concerns in regard to the problem being addressed”, including both positive and negative concerns (Guðlaugsson et al., 2020, p. 172). Naturally, in this report, interest refers to the concerns stakeholders have in regard to the development of a hyperloop corridor.

Bearing in mind these definitions of interest and power, the stakeholders are categorized under high or low power in the project, and under high or low interest in the project. These options are combined and result into four different clusters, as shown in Table 3.1.1. This method of clustering stakeholders is according to the stakeholder analysis theory of Eden and Ackermann (Eden and Ackermann, 1998).

Table 3.1.1: Stakeholder Types

Power	Interest	Stakeholder type	How to deal with stakeholder
High	High	Players	Manage closely: it is necessary to engage fully with this type of stakeholders to keep them satisfied at all times.
High	Low	Context setters	Keep satisfied: this type of stakeholders is required to be involved to a reasonable level in order to keep them satisfied but not overwhelmed with excessive communication.
Low	High	Subjects	Keep informed: information on the project needs to be provided to these stakeholders, in order to prevent conflicts and to receive advice from their side.
Low	Low	Crowd	Monitor: keep an eye on these stakeholders to guarantee that no issues are arising.

The identified stakeholders will be assigned to the different clusters. Consequently, this will be presented in a matrix, of which a template is shown in Figure 3.1.1.

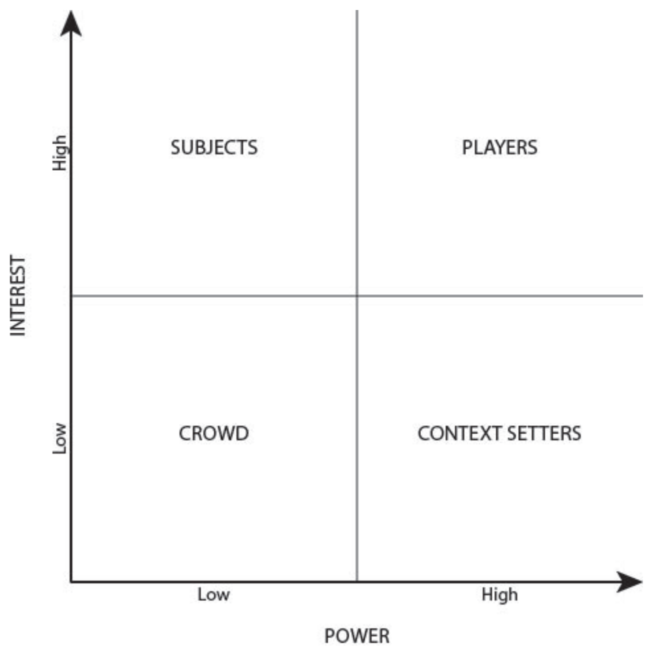

Figure 3.1.1: Stakeholder map framework, (Guðlaugsson et al., 2020).

3.2 Stakeholder Identification

In this section, the stakeholders are identified, defined and categorized. This selection of stakeholders was gathered based on a brainstorm session with experts and on literature on similar infrastructure projects (High Speed Two Limited, 2012; Feliu, 2012).

Table 3.2.1: Stakeholder identification for a hyperloop corridor.

Stakeholder groups	**Definition**	**Position**
Landowners	Landowners are those who (privately) own land in the same area where a future hyperloop corridor is assigned.	To be able to develop a hyperloop corridor on that land, it should be acquired from the private landowners. When landowners do not wish to cooperate, problems arise in the allocation of the hyperloop tube. This makes them a highly interested and powerful stakeholder.
Hyperloop Companies	Hyperloop companies are private businesses that develop and manufacture hyperloop technology such as the pod and track.	Hyperloop Companies play a significant role in the development of a hyperloop corridor. They can sell their products to the commissioning party of the hyperloop corridor in question, or even to other international hyperloop parties. If they have sufficient investors, it might also be the case that a private hyperloop company will decide to become the main organizer of a hyperloop corridor, whilst implementing its own technology.
Investors	Investors are agencies that invest in a hyperloop project and are often involved by the commissioning party, either public or private, in order to financially realize a hyperloop corridor.	Investors have a dominant role in the development of a hyperloop corridor. Their main interest is the profitability of the corridor, which will be an important factor in the decision-making process of the development of the hyperloop.
Contractors	Contractors facilitate and organize the complete construction, maintenance and operation of a hyperloop corridor.	Contractors organize the actual execution and operation of the hyperloop corridor, making them closely involved with the project. The contractor with the best design and offer will be awarded the job by the commissioning party. On a more zoomed-out organizational level, they have rather limited impact.
Construction Companies	Construction companies execute the construction of a hyperloop corridor.	Construction companies are an interested party in the development of a hyperloop corridor. A hyperloop corridor is a mega infrastructure project which could generate large revenues for these companies. The international nature of the infrastructure could also interest construction companies as it enables them to sell their skills and materials on a large scale.

(Continued on next page)

Table 3.2.2: continued

Stakeholder groups	Definition	Position
Residents	Residents are people who live near the hyperloop tube and stations and experience direct impact from the hyperloop corridor.	Residents are directly affected by a hyperloop corridor in a certain location by means of disturbance of view, noise and vibrations. Moreover, the mobility of people living near the corridor can be improved by the hyperloop corridor. This makes residents a highly interested party, yet with limited direct influence in the project.
Commuters	Commuters are people who have to travel a certain distance on a frequent basis to get to their work.	Commuters are an interested party, as the corridor selection determines the accessibility of certain places to work and live.
Social Recreational Travelers	Social recreational travelers are people who travel to places for recreational purposes, such as tourism, visiting family and friends, going for dinner, shopping etc.	For this group, the implementation of a hyperloop corridor is of importance due to the increased mobility of certain places as a result of the hyperloop. Therefore, social recreational travelers are an interested party in this project. Yet, it can be expected that social recreational travelers will not form a large share of the passengers of the hyperloop, meaning that their impact on the corridor, in terms of revenue for instance, is limited.
European Commission	The European Commission is the executive body of the European Union. Certification, legal procedures and perhaps funding for a European hyperloop corridor would be organized by this institution.	The European Commission is an essential player for the realization of a European hyperloop corridor. International political and technical differences with regards to hyperloop infrastructure need to be resolved by the European Commission through universal standards, laws and regulations. This makes the European Commission a stakeholder of high interest and high power.
Ministry of Infrastructure	The Ministry of Infrastructure of a country can play different roles in the realization of a hyperloop corridor. It is likely that the Ministry will be a primary investor and organizer of a corridor in that country. Moreover, laws, licenses and regulations imposed by this Ministry will affect the realization of a hyperloop corridor. The Ministry could be in charge of assigning an institution to facilitate certificates and other safety measurements (Arup et al., 2017).	As the main organizer, investor and responsible institution for the implementation of a hyperloop corridor on a national level, the Ministry of Infrastructure fulfills a defining position in terms of interest and power.
Ministry of Economic affairs and Environment	The Ministry of Economic Affairs and Environment sets laws and regulations in terms of emissions and sustainability of a certain infrastructure project. Moreover, it can grant subsidies to worthwhile projects.	Through setting laws and regulations and potential funding, the Ministry of Economic Affairs and Environment is another key player in the development process of a hyperloop corridor.

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Table 3.2.2: continued

Stakeholder groups	Definition	Position
Environmental activist groups	Environmental activist groups strive for the minimalization of harmful impact on the environment of infrastructure projects such as a hyperloop corridor.	Environmental activist groups are likely to have high interest in the project as the placement of a hyperloop corridor impacts surrounding nature by emissions caused by production and by disturbing habitats with the built infrastructure and noise and vibrations.
Hyperloop Student Teams	Hyperloop Student Teams work on the development of hyperloop technologies and prototypes around the world.	Hyperloop Student Teams are interested in the implementation of a hyperloop corridor as it realizes the technologies designed and tested by them.
Local governments (municipalities)	Local governments play a role in the development of a hyperloop corridor through local laws and regulations and are also part of the decision-making process around the implementation of a hyperloop corridor.	Local governments are likely to be highly involved. The hyperloop tubes will have an effect on the areas it passes. Local governments of those interlaying regions can have demands and impose restrictions on the location and spatial integration of the corridor.
Employers	Employers are located around the station and tubes of the hyperloop corridor.	These employers have an interest in the development of a hyperloop corridor in their surroundings as that specific region can become more accessible for a wide range of skilled employees.
Maintenance companies	Maintenance companies facilitate regular preservation of hyperloop infrastructure.	Maintenance companies are an interested party as they have the responsibility for keeping a large infrastructure system with new techniques running and of high quality, which impacts the lifespan of the structure. Yet, on an organizational level, their influence is rather limited.
Certification Authority	A certification authority is required to regulate licenses and certificates for the construction of hyperloop corridors. An institution like this will likely fall under the international responsibility of the European Commission or a Ministry of Infrastructure, in order to guarantee standardization and unity amongst a European hyperloop network.	A certification authority is a crucial part of the development process of hyperloop corridors. This institution is in charge of setting and testing standards that the hyperloop corridor is required to meet, which has large consequences for the development phase. This makes the certification authority very relevant in terms of interest and power.
Current Modes of Transport	Current modes of transport are the rail, marine, road and aviation sectors .	These current modes of transport have an interest in the development of a hyperloop corridor as it could become a potential competitor but could also become integrated within the current modes of transport. They are also powerful stakeholders as they are key players in the transport market and can impact whether a hyperloop would be feasible within this market.

3.3 Stakeholder Map

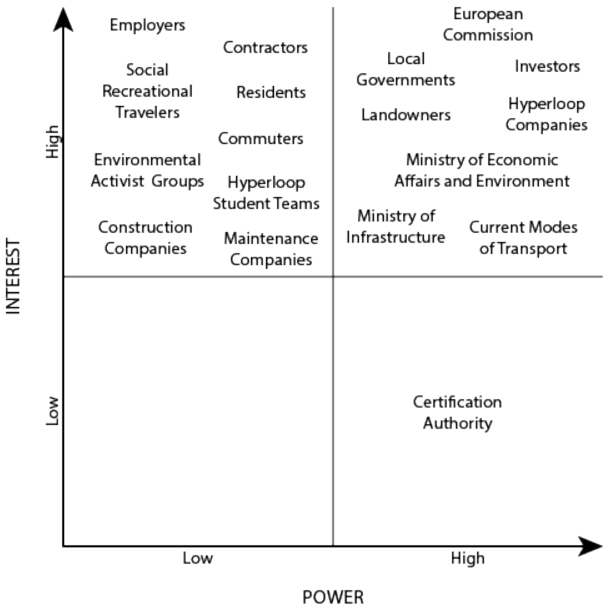

Figure 3.3.1: Stakeholder Categorization Map.

3.4 Participation Strategy

As demonstrated above, there is a large number of stakeholders involved in the development of a hyperloop corridor between two cities. With varying degrees of power and interest, the stakeholders form a complex web. In essence, the identified stakeholders can be categorized into three stakeholder sectors; private sector, public sector, and a civic sector (South et al., 2018). The latter consists of the stakeholders that are part of the general public, including environmental activist groups and users of the hyperloop. These different actor groups operate by varying objectives, perspectives and perceptions of social, environmental and economic values (South et al., 2018). Smooth management of these stakeholders is therefore crucial, particularly due to the multidisciplinary nature of hyperloop development.

The hyperloop is a completely new form of transport, meaning that an entire infrastructure system has to be designed and implemented. There are no examples of previously executed hyperloop projects that project managers and investors can use to anticipate and build upon. Furthermore, due to the considerable size of the hyperloop infrastructure, the ownership and financing of the system could have a fragmented nature in which multiple investors and responsible parties, both private and public institutions, will be closely engaged. Co-ownership and co-financing collaborations are rather likely to be necessary for a hyperloop corridor to come to reality, yet it can lead to complicated and intertwined stakeholder relationships. These types of collaborations often operate over long life-cycles, with multiple phases where varying involvement from stakeholders is required, making these dynamic collaborations exceptionally demanding to coordinate (South et al., 2018).

For a large share of the stakeholders, achieving financial revenue is the prominent desired effect of a hyperloop corridor. According to Feliu, “local economic development depends on the organizational ability of the local stakeholders themselves, which allows for the optimal use of knowledge, work and capital available” (Feliu, 2012, p.294). Moreover, effective coordination of the stakeholder groups can limit friction and opportunism amongst them and can minimize the extra time and budget that the project requires (South et al., 2018). Simply put, the structure and organization of stakeholders in a large infrastructure project has a major impact on the eventual outcome of the project.

There are many roles and tasks to fulfill in the road towards a finished hyperloop corridor, including financing, managing, licensing, designing, constructing, and maintaining. This participation strategy is presented in order to create clarity in this multi-disciplinary project and to maximize the accomplishment of the desired goals. It will provide a stepwise approach of the different necessary phases in the development of a hyperloop corridor, along with its corresponding responsible parties.

An essential part of the development of a hyperloop corridor is creating a detailed infrastructure planning and an infrastructure delivery plan. These documents are strategic tools which benefit the integration between the involved public and private parties and assist in establishing collaboration agreements (Morphet, 2009). Furthermore, they structure the identification of the infrastructure requirements, costs, funding methods and different responsibilities across stakeholders. As a framework for these future hyperloop infrastructure plannings and delivery plans, this participation strategy first of all proposes several collaboration structures for the project. Secondly, the development process of a hyperloop corridor is presented through five phases (South et al., 2018). For each phase individually, the varying tasks, deliverables and possible responsible parties are discussed. By these means, this participation strategy aims to create a concrete overview of the different steps and roles which need to be fulfilled in order to deliver a functioning hyperloop corridor in an efficient and conflict-free manner.

3.4.1 Collaboration Structure

Before diving into the different phases and tasks within the development of a hyperloop corridor, varying collaborative structures need to be analyzed on their suitability for creating an infrastructure project of this significant scope. It must be stated clearly that there is not just one collaborative structure that fits the development of hyperloop infrastructure. What structure applies best depends on several factors. For instance, the extent to which a national government wishes to be involved in the development of large infrastructure projects differs considerably per country. Moreover, the presence of large commercial actors who are interested in investing in hyperloop infrastructure is a variable for different countries. Therefore, this section does not necessarily aim to prioritize one collaborative structure over the other. Instead, merely an overview of the potentially suitable structures is offered. Based on more specific characteristics on the organizational structure of an individual country, commissioning parties can assess which structure would be most beneficial for realizing a hyperloop corridor in their nation as part of a European hyperloop network.

3.4.2 Hyperloop Organization On A European Scale

It should be mentioned that the international nature of the proposed hyperloop network in Europe brings along additional complexities. It is not simply a large infrastructure project requiring investments which needs to be organized and executed. A functioning hyperloop system in Europe will only be brought to reality if it meets strict international agreements and regulations on the technique, safety and operations of the system. More importantly, the entire network will have to run on the same technical designs and dimensions throughout the whole of Europe. Currently, multiple commercial hyperloop companies are developing different hyperloop technology and structures across the continent. Eventually, these separate systems will have to come together into just one well-functioning, standardized hyperloop system.

The required convergence of separate hyperloop technologies for a European hyperloop network strongly calls for an overarching institution that will guide and certify the standardization of hyperloop infrastructure across the continent once the technology is ready. This institution is the designated actor to initiate the first steps of the development of a European hyperloop network and bring relevant parties together. As it is most effective to make use of existing institutions with authoritative and regulatory capabilities, this report proposes that this institution should be established within the European Union.

EU Motivation

Before discussing through which means an EU institution could provide these standardization and certification requirements, it should be indicated for what potential reasons the EU would be interested in being involved in hyperloop development in the first place. It must be mentioned that the following reasons are non-exhaustive. Actual analytical models will have to support these assumptions.

First of all, the hyperloop offers an energy-efficient and, provided that only green energy is used, sustainable alternative to short-haul flights. Considering the European Green Deal, which aims for a climate-neutral Europe in 2050, the EU will be actively searching for innovative technologies which contribute to achieving this goal (Sims and Schaeffer, 2014). As the transport sector is a major contributor to CO_2 emissions, the hyperloop could make a significant difference in cutting CO_2 emissions in Europe, under certain circumstances.

Secondly, by implementing a Europe-wide hyperloop network, the EU can work on enhancing mobility and accessibility throughout the continent. Connecting member states and improving their social and economic cohesion in a sustainable manner belong to the core functions of the EU. In order to make this argument convincing, it must be shown clearly how a hyperloop network can be complementary to the existing HSR and aviation networks in which the EU already invested. A hyperloop network that can easily cross borders and connects the centers of major European cities facilitates the additional exchange of knowledge, skills and capital to a new extent. Moreover, due to its superior connectivity, EU member states could become more attractive for investments and companies to locate themselves in.

Lastly, by becoming the frontrunner of the development of this innovative form of transport, the EU could improve its position on the world stage as a European hyperloop ecosystem could function as proof of its excellent technological and logistical capacities in the field of infrastructure. Hereby, the EU can grasp the opportunity to strengthen its international competitive position. In addition, in the short term, initiating hyperloop development can also lead to beneficial spin-off technologies which can add innovations to other sectors in the EU.

Actual interest by the EU in a hyperloop network has been shown, as the hyperloop was mentioned in its 2021 Mobility Strategy and Action Plan (European Commission, 2020). In this document, the European Commission refers to the hyperloop as a technology which has the potential to improve future mobility in the EU, which requires the EU to put in place a favorable environment for its development (European Commission, 2020). The reference to the hyperloop in this EU document illustrates how the hyperloop is in fact 'in the picture' to a certain extent in the European Commission. Moreover, granted subsidies by the European Commission to Hardt Hyperloop further indicates the growing involvement and interest of the EU in the hyperloop (European Commission, 2021).

In short, potential arguments which root for a European hyperloop network initiated by the EU, as well as early-stage involvements of the EU in hyperloop development have been mentioned. In the case where the EU is definitively convinced of the benefits of a European hyperloop and these prior forms of support evolve into the actual initiative and coordination of the development of a European hyperloop network, it is of essence that this international network is organized with a top-down approach.

European Hyperloop Agency

As previously mentioned, a well-functioning hyperloop network in Europe requires an overarching authority from the EU. In this report, this proposed overarching institution is named the 'European Hyperloop Agency'. The following section will briefly discuss through which actions this agency could guide the development of a hyperloop network in Europe.

First of all, the 'European Hyperloop Agency' can be the initiator of the development of a European hyperloop network, stimulating member states to join. The agency can set this in motion by creating favorable conditions for developing and implementing hyperloop infrastructure, in terms of facilitating testing of technical systems but also in terms of lifting legal restrictions where possible. Technical and legal frameworks from the agency can further guide this process of development. Building on the existing authority of the EU, the agency has the reach to connect the different national hyperloop organizations, both public and private, who regulate and organize hyperloop infrastructure within their own countries. By these means, an international organizing web of commissioning parties for hyperloop infrastructure in Europe is created, on both European and national levels.

Secondly, the agency is essential for the standardization and certification within the European hyperloop network, which needs to take place in an early stage of the development of the network. It can impose safety and technical standards and control the issuance of certificates and licenses to hyperloop vehicles and infrastructure corporations that wish to build or utilize the European hyperloop network. Through this top-down approach, certification and legislation of hyperloop infrastructure within Europe will be organized centrally, resulting in a unified infrastructure system with certified technologies and levels of safety. In this way, the 'European Hyperloop Agency' ensures the EU-wide accessibility of the network for hyperloop vehicles from different member states with proper safety standards, enabling them to cross borders smoothly.

Lastly, the 'European Hyperloop Agency' can play a role in the financing of a European hyperloop network. In the early development phase, in which hyperloop technology itself is being designed and tested, the EU can subsidize companies working on these technical innovations, as is happening on a small scale already (European Commission, 2021). The EU can support the financing of the hyperloop system more substantially through the budget of the Trans-European Transport Network (TEN-T) (European Commission, 2022). This EU policy is responsible for operating and implementing physical connections, in the form of railways, waterways, roads and airports, between member states in order to facilitate the smooth transport of people and goods within the EU, without any barriers (European Commission, 2022). In addition to the construction of networks of existing modes of transport, TEN-T also supports the development of innovative forms of mobility whilst aiming to minimize the environmental impact of transport. To execute this policy, the European Commission funds certain EU-wide infrastructure projects which contribute to the 'Core Network' which connects member states. If a European hyperloop network were included in this envisioned Core Network, it could (partly) receive funding from the European Commission for implementing the network. The extent to which the EU will eventually get financially involved is likely to rely on the amount and nature of benefits the EU sees in the hyperloop. Moreover, it depends on the willingness of national governments and private sector companies to invest in a European hyperloop network.

This report deems a ‘European Hyperloop Agency’ a realistic solution for standardizing hyperloop infrastructure in Europe as the equivalent institution for railways within the European Union has been proven effective thus far in facilitating similar goals. This concerns the European Union Agency for Railways (ERA) (European Union Agency for Railways, 2017). This institution intends to guard international safety and accessibility of railway throughout the EU. Their goal is to work towards a united, integrated railway system which all member states and their specific trains can utilize (European Union Agency for Railways, 2017). In addition, standardization within this European network is enforced by the ERA. The institution sets norms on safety within railway in Europe, which are implemented through safety licenses which rail corporations are required to obtain in order to use the European rail network. Hereby, the agency strives to facilitate the authorization and certification of railway on a European Union scale.

The actions of the ERA concretely exemplify how a similar institution for the hyperloop in Europe could actively guide the necessary standardization and certification within a European hyperloop network. The involvement of the ‘European Hyperloop Agency’ could even be improved, compared to its railway-equivalent, by getting involved already in the earliest stages of certifying, designing, constructing and operating the hyperloop system.

In short, as the European Union has shown interest in a hyperloop system, supported by its role in the 2021 Mobility Strategy and Action Plan, and has the required authoritative and regulatory values, as demonstrated by similar EU-institutions, this report views the European Union as the suitable leading actor for initiating, standardizing and certifying hyperloop infrastructure within Europe.

3.4.3 Hyperloop Organization On A National Scale

After the development of a European hyperloop network is initiated and commissioned by the European Union, a large share of the actual funding, implementation and construction will come down to governments and companies on a national scale. This has to be executed on a national scale within the legal and technical standards and norms set by the EU. It is expected that in the EU, it will be collaboratively be determined which cities will be connected by the network, but how and where this route is implemented by the interlaying countries predominantly depends on the governments of those member states. The EU could provide the member states that are part of the proposed network with a collection of standards which the infrastructure must suffice and perhaps financial aid, whilst the further construction and financing of the hyperloop network in the individual countries has to be organized on a more local level.

When zooming in on the organization of hyperloop infrastructure on this national level, it is questionable whether a single party will have the intention and resources required for taking on the responsibility to finance, operate and maintain the infrastructure system. Apart from a significant budget, regulatory tools, innovative strength, and legitimacy are also necessary to establish a hyperloop corridor that generates both commercial and societal benefits (Kishk, 2020). On a national level, there are three main collaborative structures that could initiate and take on the further responsibilities of organizing and regulating a hyperloop corridor: the organization of a hyperloop corridor could be run by a public party, a private party, or a combination of private and public parties. This report will go into these three possible forms of collaborative structures in order to give insight into the possible methods of how the hyperloop could effectively be realized within individual countries. For each collaborative structure, possible arguments for getting involved in hyperloop infrastructure will be discussed, as well as financing and operating methods.

Public Party

The extent of the involvement of a public party, in this case a national government, strongly depends on the wider benefits that the government sees in implementing a hyperloop corridor in its country. For many national governments, the hyperloop can be seen as a solution to current problems in existing modes of transportation. Similar to the EU’s reasoning behind a hyperloop, national governments can exploit the hyperloop as a means for achieving climate goals and for enhancing mobility and accessibility within their nation. Investing in hyperloop development could also be beneficial for a national government by attracting smart people and companies, creating a new national export product and through innovation spillovers to other sectors (van Nieuwenhuizen Wijbenga and Keijzer, 2020).

If a national government, stimulated by the proposed network of the EU, is in fact convinced of the implementation of a hyperloop corridor in its country, it can be an option that the full responsibility of the funding, constructing, owning and operating is in the hands of the national government. This way, the government in question can ensure that the project benefits its wider economic and social aims. There are certain other advantages to publicly regulating, financing and operating a hyperloop corridor.

First of all, the government has the authority and regulatory tools that are required for implementing such a large infrastructure project. This authority will contribute to the coordination of this complex infrastructure project. In addition, a national government can guarantee the implementation of technical and safety standards set by EU institutions, to guard the accessibility and safety of the hyperloop corridor. Secondly, simply put, governments are in control of a wide range of resources of their nation. Resources in terms of money; governments are the institutions that can borrow money as cheaply as possible, compared to private parties. But also, resources in terms of land; land needs to be acquired for the construction of tubes on those grounds. Lastly, full-government control over the hyperloop corridor will focus on increasing the life span of the infrastructure as long as possible. More long term economic and social goals which benefit a wider target group than just the actual users of the infrastructure will be pursued more actively by the government. Governments are therefore less restricted by the outcome of just the business case of a project, but also take these wider effects into account when looking at the feasibility of the infrastructure.

If a national government were the commissioning party of the hyperloop corridor within its own country, it would be responsible for setting out calls for tenders in order to assign architects, structural engineers and contractors to the project. Moreover, hyperloop companies which produce and deliver the hyperloop pods need to be assigned. Together, these parties will execute the design and construction of the corridor as commissioned by the government. In addition, the operation and maintenance of the corridor can also be transferred to a contractor. In this way, the government delegates more practical tasks to separate private companies, whilst maintaining control over the time frame, budget and stakeholders of the project (Kishk, 2020). This structure with a national government as commissioning party is further illustrated by Figure 3.4.1.

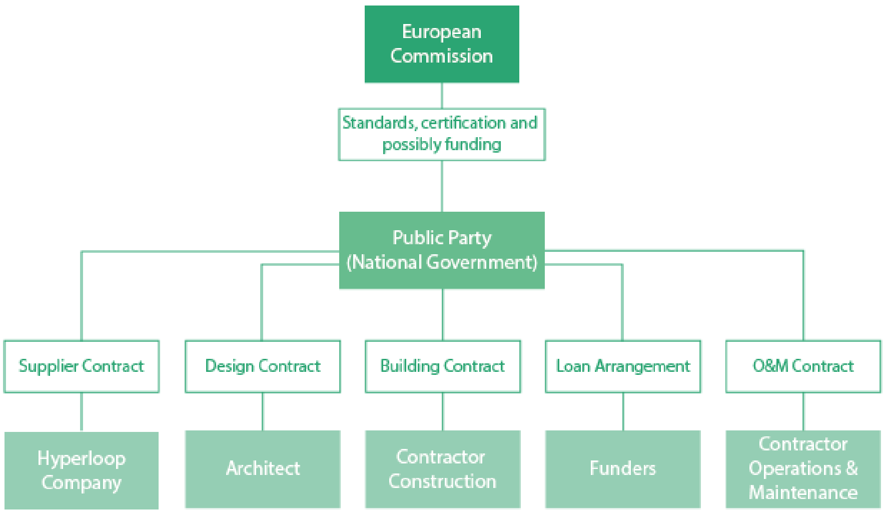

Figure 3.4.1: Public Hyperloop Framework, (Kishk, 2020).

In this scenario, where the government takes full responsibility for the implementation of the corridor, the costs of the project would be carried by the national budget, largely consisting of tax money. This places considerable pressure on the available resources of a government. Presumably, a national government will have to approach lenders to borrow money from in order to fully cover the costs of the project. After the implementation of the hyperloop corridor, the large initial investment costs will partly be recovered by the actual users of the infrastructure. However, there is a plausible chance that a reasonable user fee will not cover the very substantial initial investment costs, meaning that not only the users of the infrastructure will carry the financial burden. Therefore, this gap will have to be closed by the national budget, including taxpayers' money (Kishk, 2020).

Apart from the mentioned benefits that a fully-government run hyperloop implementation brings along, there are certain difficulties along the road as well. The lack of investment from the government can form a major issue. Governments hold strict control over their national budgets and aim to keep taxation as low as possible (UNECE, 2012). A national government can only spend its available money once, meaning that if it would decide to finance a hyperloop corridor, other socially relevant purposes such as healthcare or education cannot be assigned this money anymore. This might lead to critical responses from parts of society. Moreover, governments can morally question whether it is fair to rely on taxpayers' money to compensate for the large investment costs of the hyperloop corridor, whereas not every taxpayer might be capable of actually using the corridor. Secondly, specific skills and hands-on experience that usually comes from private companies are absent when the hyperloop corridor is completely coordinated by national governments. Innovative technologies and specific expertise coming from the private sector play a less dominant role in this scenario, whereas they can strongly benefit the outcome of the project. This could potentially lead to inefficient planning and implementation of the project. Moreover, as the government does not have a profit motive with this project, certain forms of inefficiency and lack of discipline could arise. Lastly, by taking on the responsibility for implementing a hyperloop corridor, a government takes on a wide range of economic and political risks, which would conflict with a risk-averse attitude national governments would often want to pursue.

Private Party

Alternatively, it can occur that the private sector wishes to be the primary commissioning party of a hyperloop corridor within a specific country. This means that this private party, or collaboration of multiple private institutions, takes up the responsibility for coordinating, financing and operating the implementation and functioning of a hyperloop corridor. In this scenario, the private sector party would spread invitations for tenders to contractors for the design, construction, operation and maintenance of the hyperloop corridor, which all would be controlled by the private sector party. This structure is shown in Figure 3.4.2.

The rationale for the private sector for investing and participating in the realization of a hyperloop corridor would be to generate profit. In order to answer to this profit motive, the project needs to have a positive business case, implying that the expected income that the infrastructure project will generate will clearly outweigh the expected costs. In order for a completely privately funded hyperloop corridor to be realized, the business case must be positive without supplementary subsidies and financial aid from government institutions. In the case where the private sector views the hyperloop corridor as profit-generating, it can decide to get involved and invest in the project. The implementation of a hyperloop could benefit from private sector involvement for several reasons. As the project is driven by the aim to generate profit in the short term, the efficiency of the process of implementation will be of high importance for the commissioning party. This could lead to an accelerated construction timeline and a more disciplined approach. Moreover, there will be direct access to the expertise and skills in different technologies that are required for realizing the corridor, enhancing the quality and innovation within the project.

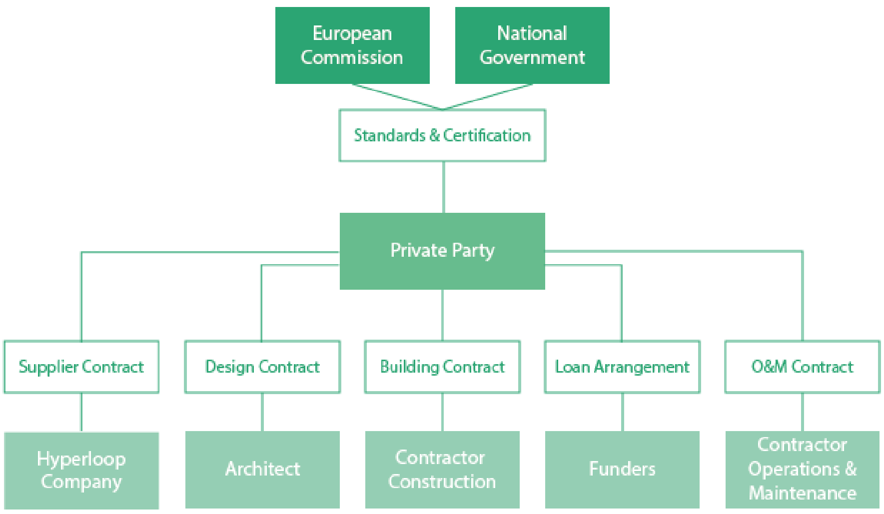

Figure 3.4.2: Private Hyperloop Framework.

However, the private sector will be subject to certain boundaries determined by the public sector. Despite the fact that the private sector would be the main organizer and funder, it will still be tied to the legal and technical restrictions set by government agencies. The infrastructure that is implemented is required to meet the safety standards imposed by the EU and national governments. Furthermore, in order to acquire land to place the infrastructure, agreements and licenses are required from local governments. These restrictions can lead to complexities and delays in the process. The potential lack of overall authority of the organizing private sector party might further complicate the development of the project. Additionally, the private sector party is exposed to many risks by implementing a hyperloop corridor. The success of the project relies on rather fluctuating economic conditions, of which the private sector parties hold no control. There are multiple other political and economic uncertainties which affect the success rate, as the private sector does not receive financial or political support from government agencies in this scenario. Moreover, wider benefits of the hyperloop corridor for a national economy or society are not necessarily of interest to the private sector who is investing in the project. This could prevent long term wider beneficial effects that the hyperloop could have from being actively pursued.

Combination Of Private And Public Parties

From the previous sections on public and private parties, it can be concluded that both scenarios come with certain benefits and issues. A conclusion that can be drawn is that it is extremely challenging for a single party to provide the required investment costs, authority and skills all at the same time whilst being prone to a wide range of risks. Therefore, this report considers a combination of private and public parties as the most effective and realistic for the responsibility of the implementation of a hyperloop corridor on a national scale. Through a collaboration between the public and private sector, the authoritative strengths of the public sector can be built upon whilst benefiting from the efficiency, specific skills and investments of the private sector (UNECE, 2012). It strongly depends on the nature of a country's government as well as the available private parties what this combination will actually look like and how the different responsibilities will be divided amongst the parties. Moreover, the market conditions at the time of the development and implementation of the corridor can have an effect on the degree of involvement of the different parties.

There are several options for a collaboration between private and public parties in the development of a hyperloop corridor. This report will suggest a few scenarios, which have been discussed with external experts, in order to point out in what ways a hyperloop corridor could be realized by optimizing the involvement of both sectors. Yet, there are several other structures in which private and public parties could integrate in the development of a hyperloop corridor.

A possible collaboration structure could be that a private sector is the commissioning party whilst the government assists the project legally and financially. It is plausible that the business case of the hyperloop corridor might not be positive in the beginning, without the financial aid of the public sector. This way, the hyperloop corridor is unable to generate profit and economically compete with current modes of transport. To stimulate the private sector to pursue the implementation of a hyperloop corridor, the government could assist as follows. The public party could grant subsidies to the project which contribute to covering the investment costs and to getting the project off the ground. Besides financial aid in this early stage, the government could assist by eliminating legal and governance boundaries and by reviewing existing associated laws and regulations. Through these means, a national government could pave the way for the implementation of a new, innovative and energy-efficient mode of transport. When the realization of the hyperloop corridor is set in motion successfully and becomes competitive with other modes of transportation independently, the government could gradually cut back in granting subsidies, leaving more financial responsibilities to the private party. In this structure, the government provides a necessary financial and legal kick-start to the private sector. In addition, through this collaboration, the risks of the project are also partly carried by the public sector in the beginning stage, relieving some of this burden for the private sector.

Another collaborative structure that could benefit the implementation of a hyperloop corridor is a Public-Private Partnership (PPP). This is a collaboration between a public sector party and a private sector party, which is based on a long-term contract, making it a more fixed collaboration than the first suggested structure. This partnership strives to enhance both commercial and societal affairs. Both parties in the PPP are expected to deliver to the project by making financial contributions, such as budget, manpower, and materials, as well as making skills-related contributions such as knowledge, management, and legitimacy (Netherlands Enterprice Agency and RVO, n.d.). In a PPP, a national government is the co-organizer of a project together with a private party. The government signs a contract with one private party, stating the project specifications and the division of responsibilities and financing. Subsequently, this private party is responsible for assigning contractors for the design, construction, operation and maintenance of the corridor, which all must meet the requirements set by the government. This collaborative structure is illustrated in Figure 3.4.3.

In a PPP, the government is the main coordinator, providing authority and legitimacy (Kishk, 2020). The private sector contributes to the project by offering innovative technologies and skills, efficient management experience and most importantly, financial aid (Kishk, 2020). It depends on the nature of the PPP in question how costs are divided between the two parties. Often, this responsibility is largely transferred to the private sector, which then searches for funders of the project. A PPP structure has several advantages for the involved parties and outcome of the project. The involvement of the private sector in the financing of the projects is beneficial for the government for limiting national expenditures and the height of taxation (UNECE, 2012). In addition, expertise and innovation from the private sector increase the quality and efficiency of the implementation of the project (UNECE, 2012). Lastly, by sharing financial responsibilities for the project, risks are mitigated amongst both parties.

However, PPPs also come with certain complexities which need to be considered when opting for this collaborative structure. Often, PPPs turn out to be rather complicated and expensive collaboration structures. Extensive negotiation processes precede the PPP, as both parties need to agree on the divided burdens of responsibilities and finances (Kishk, 2020). The collaboration is based on a set contract, leading to a rather inflexible and long-term agreement (Kishk, 2020). By transferring costs and risks to the private sector, the public sector party also loses a substantial part of its control over the project, which can have consequences for the intentions and outcomes of the project. Coordinating a PPP can be rather challenging, therefore, a government should have the skills to effectively implement this approach.

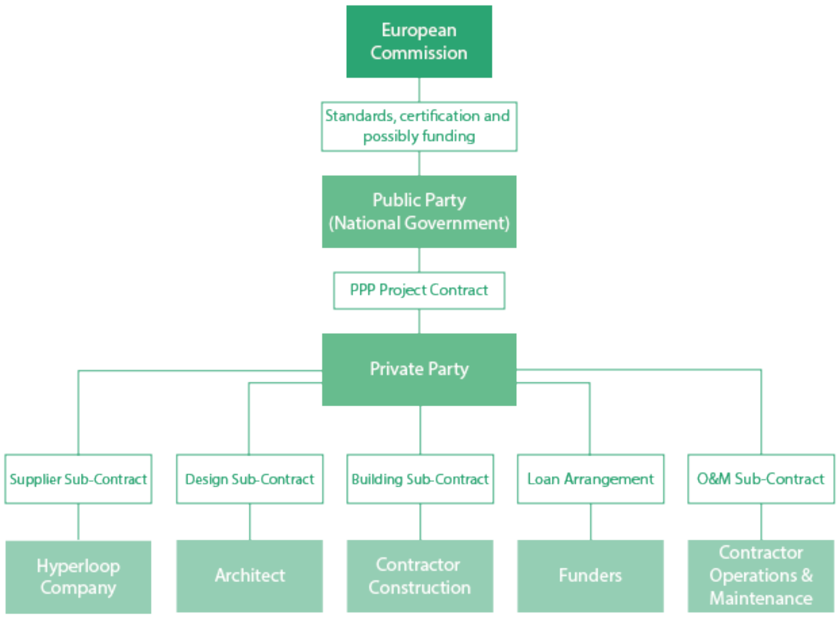

Figure 3.4.3: Public-Private Partnership Hyperloop Framework, (Kishk, 2020).

The third and final suggestion for a collaboration structure is the case where the infrastructure is run by the private sector, yet with the public sector being the dominant shareholder of that private company. The Dutch railway is organized in a similar way. The company itself is privately run, but 100% of the shares are in the hands of the national government.

By owning a large part of the shares, the government shares the risks that come with implementing and running a hyperloop corridor together with the private sector agency. This creates more favorable conditions for the private party to start the development of the hyperloop corridor. Moreover, through owning shares, the national government can make sure that not only commercial interests are being pursued through the project. By being closely involved through the ownership of the shares, the national government can also stimulate that broader economic and social effects that benefit the wider society are being achieved.

The state does not necessarily have to acquire all shares of the private company for this structure to be successful. The number of shares a national government will purchase depends on multiple factors. First of all, the market determines strongly how favorable it is to buy shares in the hyperloop company. Secondly, it depends on the extent to which a government wishes to be involved, in terms of financing and managing, in the hyperloop corridor through the ownership of these shares. This is related to the nature of the government itself. It strongly differs per country to what extent governments aim to be involved in terms of finances and management in large projects like this.

3.5 Phases

Now that various motivations and collaborative structures for implementing a hyperloop corridor have been discussed, in this section the different phases, responsibilities and end products incorporated in this extensive development process are covered. As elaborated on in the previous sections, creating a hyperloop corridor on an international scale is a project with a long life-cycle, which could take up to 10 years, involving a wide range of stakeholders which fulfill different roles.

As a consequence, the development process of an international hyperloop corridor from A to Z could become a complex and lengthy procedure. In order to provide the commissioning party of the hyperloop corridor with clarity of this process, this chapter offers an overview of the different phases, its responsible parties and key milestones that come into play in the implementation of a hyperloop corridor. It should be mentioned that the phases that will be covered apply to all three discussed collaboration structures.

In an integrated infrastructure project which is likely to be run by a combination of public and private parties, there are five different global phases that can be distinguished in the development process on a national level, which are listed below and further illustrated in Figure 3.5.1 (South et al., 2018).

- Initiation phase
- Permitting phase
- Procurement phase
- Design and construction phase
- Operation and maintenance phase

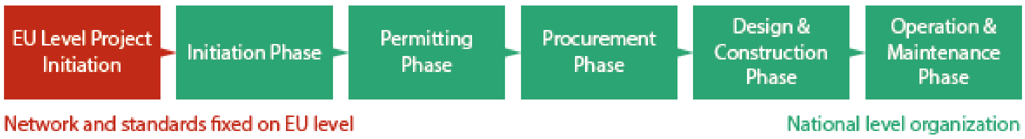

Figure 3.5.1: Phases of developing a European hyperloop corridor.

The following sections elaborate on what these phases entail for the development of a hyperloop corridor on a national scale.

3.5.1 Initiation Phase

The development of an international hyperloop corridor kicks off with the initiation phase. After the EU has initiated the development of a European hyperloop network, a public party, private party or PPP will take on the role of commissioning party on a national level. In this preparatory phase, the commissioning party initiates the first concept of the project, sets up a strategic vision and a foundational framework of boundary conditions for the project. This framework consists of wide-scale research, project requirements and feasibility studies, as further illustrated by Figure 3.5.2.

Research needs to be performed by the commissioning party on several topics. It should be examined which long-term development plans are already in place in the regions in which the hyperloop corridor should be implemented. Municipalities often have binding long-term plans which state what can be built in a certain area. The initiated hyperloop corridor should fit within these overarching development plans of national and local governments in order to be able to be realized. Research on spatial integration of the hyperloop corridor within landscapes is especially of high importance (Peek and Gehner, 2018). Moreover, as the hyperloop corridor is part of the European hyperloop network as proposed by the EU, the corridor on a national scale will have to fit within the fixed regulations and requirements set by the EU. The commissioning party of the corridor on a national scale needs to be aware of these boundary conditions. By gathering and analyzing relevant data on the project, different stakeholders can make decisions throughout the process based on valid and transparent information (OECD, 2017).

Once the context of the project is brought into focus through the performed research, the first version of the program of requirements need to be established. In essence, this crucial document lists the requirements that the project needs to meet, as stated by the commissioning party. It acts as the guiding criteria for hyperloop pod developers, architects, contractors and operators in later stages of the implementation process. The program of requirements consists of several aspects. Boundary conditions are taken into account, such as laws and regulations. Secondly, functional requirements are given: what specific functions does the infrastructure need to fulfill? Thirdly, the user requirements are mentioned, stating additional demands that are set by the users of the infrastructure, often linked to comfort. Lastly, design restrictions can be included, such as a certain timeframe or fixed dimensions.

Feasibility studies also play a large role in the initiation phase. Within the guidelines of the program of requirements, it should be analyzed how much and what kind of wealth (money, socio-economic benefits) the initiated project can generate. Business cases, cost-benefit analyses and market analyses need to be performed to examine the current economic conditions and the quantity of value that the project can create, in order to assess whether the initiated project would in fact be feasible (Peek and Gehner, 2018). According to a study from McKinsey & Company, frequently, unrealistic expectations of the benefits and costs are set at the beginning of a project, leading to financial setbacks through the course of the execution of the project (Garemo et al., 2015). The costs are regularly underestimated while the benefits are often overestimated by commissioning parties in order to make the project look more attractive, which is harmful for the outcome of the project. In order to make representative estimates of the costs and benefits of the projects, independent analyses have to be performed in this phase (Garemo et al., 2015). Moreover, in the case where these independent studies turn out positive, meaning that the project creates sufficient revenue or broader value to actually be implemented, they can truly strengthen the confidence in the project's feasibility and affordability (OECD, 2017). This is of essence for attracting investors in the project in a later stage.

When the research and feasibility studies are performed and project requirements have been established, a long-term strategic vision has to be set up by the commissioning party (OECD, 2017). This strategic vision can act as a guide on how the previously set project requirements can be achieved. It is of importance that this strategic vision incorporates the present stakeholders and their involvements and interests, as they have a significant impact on the outcome of the project (OECD, 2017). The strategic vision should also address financial requirements. Different financial needs should be prioritized by the vision and initial investment plans should be mentioned (OECD, 2017). Lastly, the strategic vision should include an initial, global infrastructure planning and delivery plan. This aspect contributes to achieving the overarching strategic vision by maintaining an overview of the different tasks and organizations involved over the course of the project (Morphet, 2009). Through this strategic vision, the project needs are taken into account and are prioritized throughout the long-term development project. In addition, by communicating this vision across different levels of the project organization, transparency of the process is stimulated from the first steps onwards.

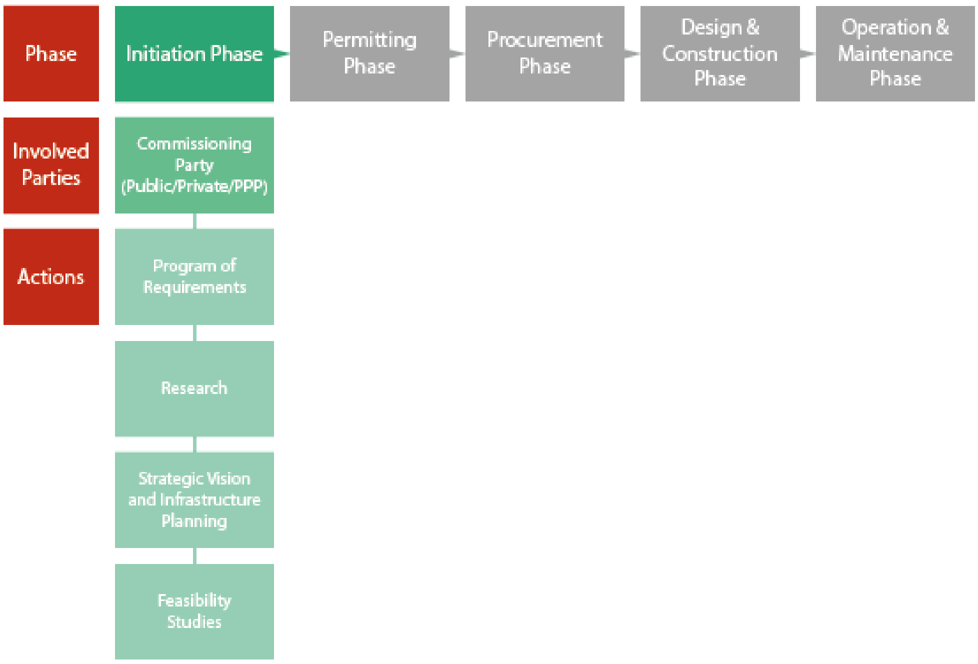

Figure 3.5.2: Initiation Phase.

3.5.2 Permitting Phase

Prior to moving on to the financing of the project and the procurement phase, the commissioning party needs to acquire permits for implementing the hyperloop corridor in specific locations. Once the initial ideas for the hyperloop corridor, based on the research, feasibility studies and program of requirements, have been established in the initiation phase, the commissioning party cannot straightly move towards designating hyperloop pod and tube developers and contractors to execute the project.

First, national and local governments will have to come to an agreement with the commissioning party on where the corridor is allowed to be placed. Not only will governments of different scales be involved in these discussions, but also other impacted stakeholders such as residents and environmental activist groups will come into play and defend their interests. Integrating a hyperloop corridor in a landscape requires the necessary space and leads to consequences for its surrounding environment and inhabitants. The diverging interests of the stakeholders involved need to be mediated and brought to an agreement. As a next step, permits can be granted to the commissioning party by the national and local governments which specifies where the corridor is allowed to be located.

As acquiring these permits forms a crucial aspect of the project, especially due to the large number of small-scale governments and other stakeholders involved, a whole separate phase in the development process is dedicated to it, of which the specific steps are outlined in Figure 3.5.3. Moreover, the entire process of acquiring these required permits might be rather lengthy, of which the commissioning party should be very much aware when scheduling the process of developing the infrastructure in the initiation phase. It occurs frequently that the period needed for receiving permits takes longer than the phase in which the project is actually being built (Garemo et al., 2015). Clearly structuring and communicating the different roles and responsibilities in this permitting process could contribute to enhancing the efficiency of this phase.

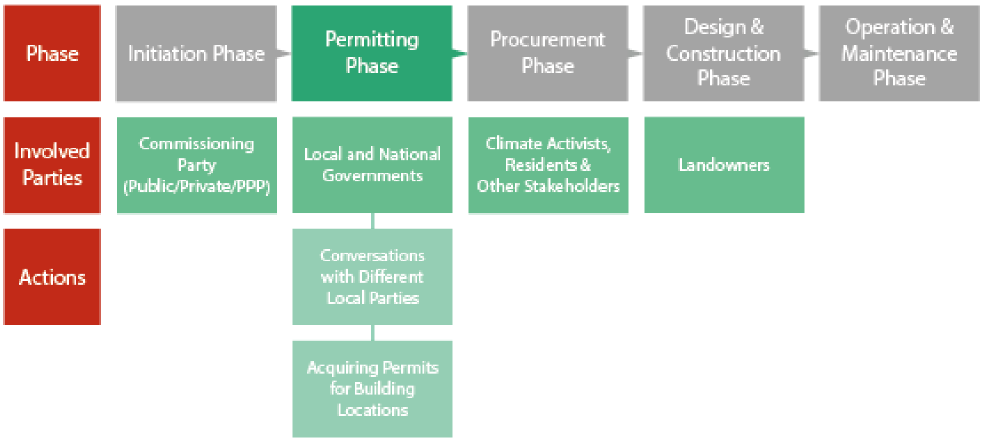

Figure 3.5.3: Permitting Phase.

3.5.3 Procurement Phase

After the necessary permits are acquired from national and local governments, steps can be taken towards the actual construction of the hyperloop corridor, including tubes and pods. These tasks will be led by different kinds of (sub-)contractors, architects and hyperloop companies which deliver pods and other subsystems. First, these various suppliers need to be notified and selected by the commissioning party of the project through a structured evaluation process in the procurement phase (Ruparathna and Hewage, 2015).

This process commences in the procurement phase when the commissioning party composes a Request For Proposal (RFP). An RFP is a document which gives notice to suppliers of goods and services with specific (technical) expertise that offers can be submitted to be selected for executing aspects of the project. In that sense, an RFP acts like an advert which announces a competitive bidding process, alerting suppliers that the commissioning party wants to procure and that they can submit a tender. The document entails the necessary information on the project, such as the program of requirements, project and business objectives and timeline (Ruparathna and Hewage, 2015). In addition, it describes the practicalities of the selection process for the suppliers, stating how and with what required documents the suppliers need to respond.

This way, potential suppliers are aware of what they would have to deliver and what they need to submit in order to be qualified for the project.

Once the RFP is published by the commissioning party, the bidding process is opened, meaning that different suppliers can hand in a financial and technical proposal. This RFP procedure is proposed in this report as it is suitable for very large infrastructure projects, such as the hyperloop, where many different executing parties come into play. For the hyperloop corridor, a wide variety of suppliers will be involved, due to the large and multidisciplinary nature of the infrastructure, including large scale stations, tubes, pods, and innovative technologies. Therefore, many different RFP's will have to be released by the commissioning party. After various suppliers have responded to the RFP's, an extensive selection procedure will follow. The submitted business proposals will be evaluated by the commissioning party, searching for the best offer, which could rely on both finances and proposed quality, among other things.

After selecting the most suitable bidder, negotiations will take place between the selected supplier and the commissioning party on the final price and terms and conditions of the project. Finally, the project contract can be awarded to the supplier and the collaborations can come to a financial close (South et al., 2018). This represents the closure of the procurement phase and the start of the design- and construction procedure. An outline of the procurement phase is given in Figure 3.5.4).

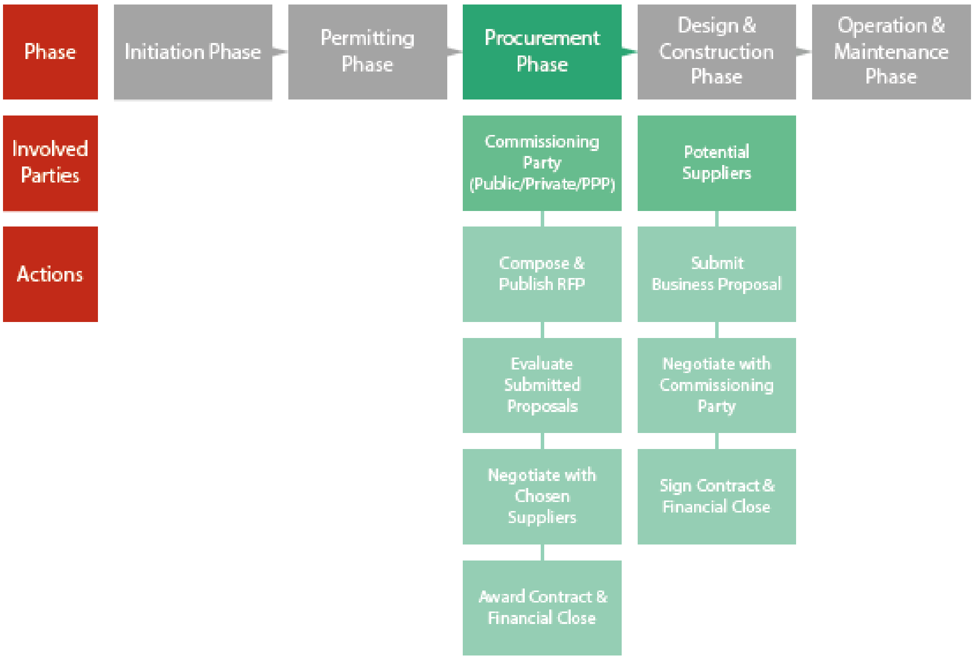

Figure 3.5.4: Procurement Phase.

3.5.4 Design and Construction Phase

Following the financial close with the different required suppliers of goods and services, the design and construction phase begins. The process of constructing a hyperloop corridor will be rather similar to other infrastructure mega projects. It is likely that there will be a main contractor who oversees the design and construction of the infrastructure, delegating responsibilities to sub-contractors. In this phase, a team of architects and structural engineers will be closely involved. In the construction process, various subcontractors will manage the purchase of materials and guide the technical approaches and plannings for the project. In addition, hyperloop companies which deliver hyperloop pods and other required subsystems such as the track will play an important role in this phase. The hyperloop pods and tracks need to be integrated within the design and construction of tube infrastructure.

Regarding the large size of the infrastructure, it must be considered that the design and construction phase takes up a lengthy period of multiple years, in which setbacks and significant delays can be expected. In mega infrastructure problems, time delays are a frequently occurring problem, leading to significant overruns of the budget (Garemo et al., 2015).

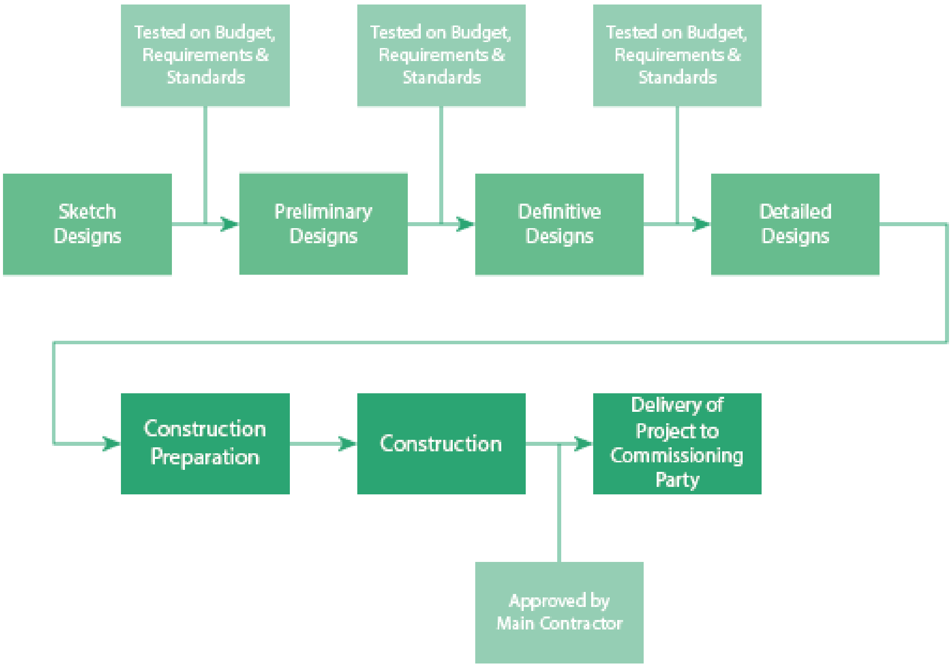

Figure 3.5.5: Design and Construction Process.

Therefore, it is essential that the main contractor, in collaboration with the commissioning party, composes a detailed planning of the entire design and construction process of the tubes, pods and internal technologies, incorporating sufficient margins in terms of budget and time to deal with unexpected obstacles. This planning should be clearly communicated with the different subcontractors, to make them aware of their responsibilities and associated timeframes. Moreover, a large number of people will be involved in this stage of the project which carry different responsibilities. Therefore, it is crucial that there is a clear and transparent top-down management approach which has direct contact lines with all levels of involved parties.

The design and construction procedure of the hyperloop corridor could be structured as follows. It must be mentioned that the hyperloop tubes and hyperloop stations will have separate, parallel design and construction processes, due to the varied sizes and nature of the constructions and its purposes. Regarding the hyperloop pods and internal technical subsystems, mainly the integration and implementation of these aspects within the tubes is of essence. The development and production of the pods will be executed by private hyperloop companies which can readily offer the finished hyperloop pods to the main contractor and commissioning party of the overarching project. It is essential that the design and construction of the pods is in line with the wider hyperloop infrastructure in order to make them compatible. Therefore, the hyperloop companies need to be closely involved in the design and construction of the tube infrastructure to make sure that the hyperloop pods can be implemented effectively. A multi-disciplinary team of engineers and architects will make a sketch design, a preliminary design, and a definitive design. From the definitive design, a detailed design can be created, which includes more information for the contractor on how the infrastructure should be constructed. This way, an effective estimation can be made of the costs of construction (Hertogh et al., 2021). In between these design iterations, the design will be tested on several criteria points, as composed by the commissioning party of the corridor. First, it will be checked whether the proposed designs fit within the available budget. Second, the designs need to be approved according to several technical and safety standards, as opposed by national and European governments and certification authorities. In addition, the permits acquired from the national and local governments which allow the commissioning party to place the construction on specific locations, need to be in line with the proposed design plans. Once the detailed designs fall within these permits and certificates and meet the technical and financial requirements, preparations for the construction phase can be initiated.

It is essential that the designs of the infrastructure project are realized in the construction phase exactly as proposed and calculated by the architects and engineers. This requires strong and visual communication to transfer the project from a design to actual construction. To prepare the construction of the infrastructure project, detailed technical drawings and maps need to be made which show exactly how the structure should be built. In addition, the required materials need to be ordered and sorted. Lastly, the construction site must be arranged and made ready for the arrival of the building materials and equipment (Hertogh et al., 2021). Thereafter, the actual construction starts. When the construction is finished, the result will be checked properly by the contractor. Once these final checks turn out positive, the project will be delivered to the commissioning party, closing the design and construction phase. Figure 3.5.5 offers a chronological overview of the design and construction process and Figure 3.5.6 illustrates the different steps, parties and tasks involved in this phase.

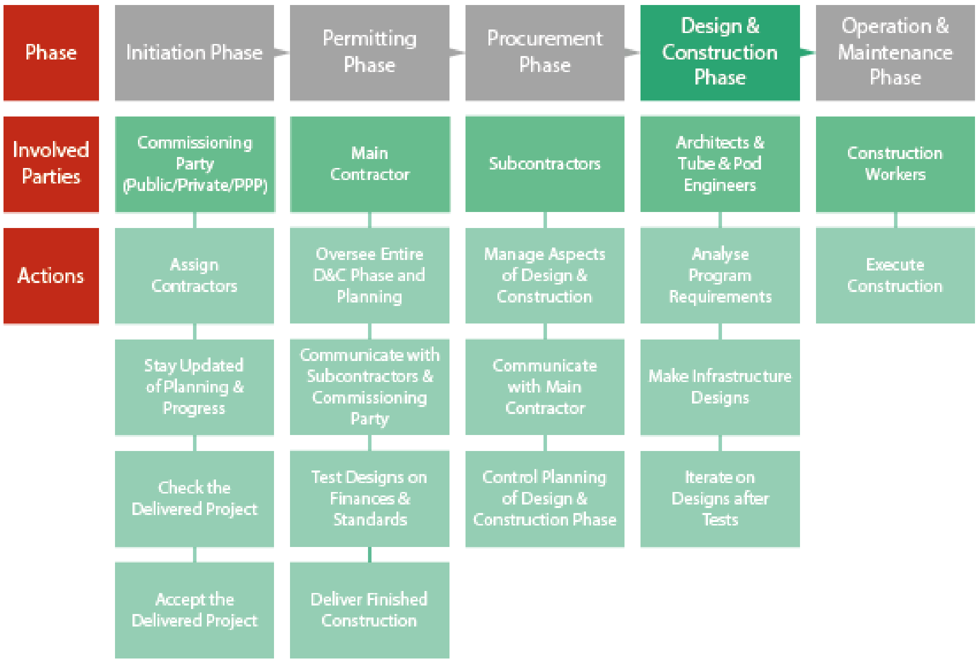

Figure 3.5.6: Design and Construction Phase.

3.5.5 Operation and Maintenance Phase

After the delivered project has been accepted by the commissioning party, the operation of the hyperloop system must be set in motion. The tubes have been integrated with the pods and subsystems in the previous phase and can be made fully operational in this phase. It depends on the collaboration structure of the project by whom the further responsibilities for operation and maintenance will be carried. It is possible for a commissioning party or owner of the infrastructure to transfer these responsibilities to a separate operation and maintenance agency or contractor. In that case, this party needs to be assigned on time, in order to make the system operational as soon as construction is finished. The different steps of this phase have been outlined in Figure 3.5.7.

The operation aspect of this phase focuses on the system being able to deliver its intended services in a reliable and safe manner. In this phase, many stakeholders are involved, who contribute to the continuous functioning and updating of the system on different levels. From a public side, the European Hyperloop Agency and national governments will play an important role in overseeing the overall functioning and safety of the system. These institutions can direct private operation contractors through certain regulations on the required operations on the system (International Coalition for Sustainable Infrastructure et al., 2022). These operation contractors are responsible for actually executing the operations. Operations entail a large number of actions, ranging from daily tasks to keep the infrastructure system functional to technical and safety assessments of the systems and collaborating with several stakeholders (World Economic Forum, 2014). These operations must ensure that a standard level of quality and safety is being met throughout the lifespan of the infrastructure. This might also include innovating through smart technologies and updating several aspects of the system.

In terms of maintenance, the hyperloop tubes will likely require less frequent maintenance than rail transport, due to the near-vacuum environment and magnetic levitation of the infrastructure system. Still, regular screening and maintenance sessions need to be planned and executed by a maintenance agency. Subsystems or specific parts will need to be checked and replaced after a certain amount of time. To avoid delays and disturbance of the functioning infrastructure system as a cause of maintenance, the maintenance activities should be scheduled far ahead and should be communicated clearly with the users of the system. This consistency in maintenance contributes to preventing damage and accidents from happening, but also enhances the reliability of the system for the users. Moreover, research could be performed into the possibilities for automated screening and maintenance of the infrastructure. As the internal systems of the infrastructure are located in a near-vacuum environment, the tubes need to be pressurized before human beings can enter the tubes to perform maintenance. This might lead to inefficiencies in terms of energy and time.

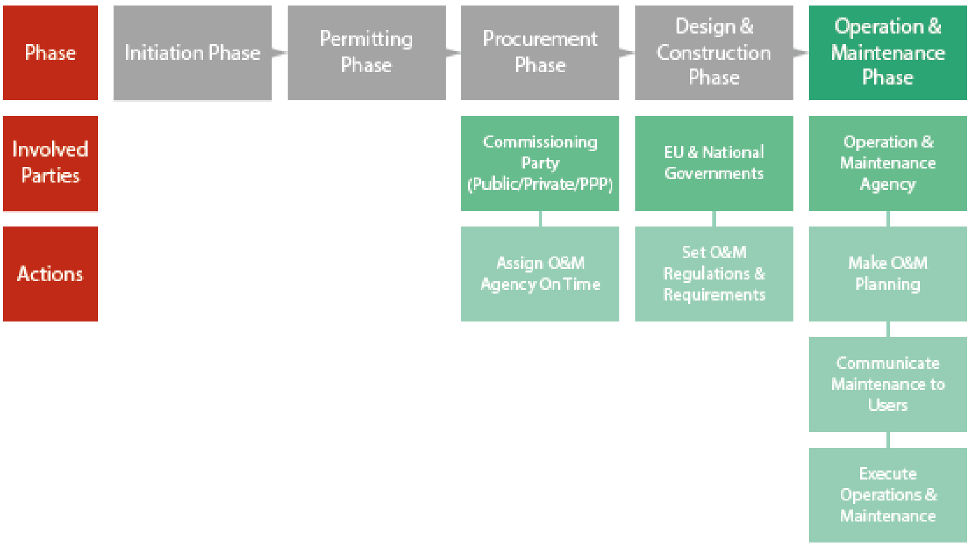

Figure 3.5.7: Operation and Maintenance Phase.

Chapter 4

Business Case

In Chapter 2 it was found that the hyperloop is characterized by a high speed, large investment costs and the ability to cover large distances in a very short time with very low energy usage. As Delft Hyperloop, we believe that it is best to implement a hyperloop corridor between two large, prosperous cities that are quite a large distance apart. In the case of Europe, these cities are likely to be in different countries, which would make the hyperloop corridor an international connection.

The main benefits of the hyperloop are a more direct connection between the cities that have a station and a large profit in travel time. The hyperloop serves, thus, to create an even better connection between cities. Because of these goals that the hyperloop aims for, the main target audience of the hyperloop can be recognized as commuters, business professionals and leisure travelers, who will use the hyperloop, for example, to reach their holiday destination. When choosing two cities that would benefit from a hyperloop connection, it is important that there is sufficient demand for a better, faster connection from this target audience.

In this chapter the main considerations are discussed that are important for private investors and stakeholders. Before any of these stakeholders would want to invest in the new infrastructure of the hyperloop, there needs to be a good business plan. This chapter does not give a fully worked out business model for the hyperloop. Instead it provides clarity on the order of magnitude of costs that are to be expected, and the most likely source of revenue with respect to the expected demand. Ideas on cost and revenue were partly established thanks to discussions with experts from TNO and the TU Delft faculty of Technology, Policy and Management.

Also included in this chapter is a market analysis for the hyperloop with the competitors of the passenger transport market that a private investor in the hyperloop needs to consider. Lastly, a compact investigation will be done into alternative uses of the hyperloop infrastructure that could make its construction more attractive under the header "Multi-use of Infrastructure". To give more tangible results, a business case of a hyperloop corridor between Amsterdam and Paris is worked out in Appendix C.

4.1 Costs

The costs of hyperloop infrastructure and operation have been briefly introduced in Section 2.6. In this section, the different expenses that come with building and operating the hyperloop will be assessed more thoroughly. Three different cost stages will be discussed: the development of the technology and infrastructure, the manufacturing and construction of all components and the operation and maintenance of the system.

4.1.1 Development Costs

The development of hyperloop technology is already well underway, with multiple companies trying to build a full sized pod that could reach speeds up to 1000 km/h in a vacuum environment. These companies are funded through investors acquired by the company itself or potentially by governments to fast track implementation. It is therefore assumed that a future commissioning party of the will most likely not have any costs due to the development of hyperloop technology and infrastructure.

4.1.2 Capital Costs

The capital costs that come with the manufacturing and construction of hyperloop infrastructure are introduced in section 2.6. Capital costs include (AECOM, 2020, Arup et al., 2017):

- Two-way tube
- Tunnels and/or pillars
- Guideways
- Switches
- Airlocks
- Stations and depots
- Vacuum infrastructure
- Power supply facilities
- Support facilities
- Sitework
- Land acquisition
- Hyperloop vehicles (pods)
- Project management
- Contingencies

There have been multiple estimations on the price per kilometer of the hyperloop, ranging from 13.3 million USD$/km (11.5 million EUR€/km in 2022) (Musk, 2013) to 45 million EUR€/km (Delft Hyperloop V, 2021b). This difference in estimations is due to the number of the above aspects that are taken into account when making the estimation, as well as better insights into the costs of certain aspects through the development of hyperloop technology and infrastructure over recent years.

There are a few things to note here. First, the capital costs of the hyperloop guideway have a great dependency on the propulsion technology chosen for the hyperloop system. There are two types of propulsion systems that are assumed to be suitable for the hyperloop, the linear synchronous motor (LSM) and the linear induction motor (LIM), which are introduced in section 2.5. The LSM uses active components in the track, resulting in higher capital costs than when the LIM is used, since hundreds of kilometers of track need to include these active components. The LSM does have a higher energy efficiency, thus cutting costs on energy consumption.

Secondly, capital costs also vary with the vertical alignment of the tube. Placing the tube underground requires tunnels to be dug for the tube to run through, which adds substantially to the capital costs (Delft Hyperloop V, 2021b). The same goes for placing the tube on pillars above the ground, the costs of which will be somewhere in between on-ground and underground alignment.

Lastly, infrastructure cost projections are often inaccurate, with a large share of projects being underestimated in total costs. Research shows that up to 45% of rail projects exceed their estimated budgets (Day and Harvey-Rice, n.d.), meaning that current cost projections for hyperloop infrastructure are likely to be too low. For example, the HSL-Zuid high speed rail line between Amsterdam Schiphol Airport and Antwerpen was projected to cost 3.4 billion EUR€ in 1997. When evaluating all costs in 2015, the project ended up costing 7.3 billion EUR€ after completion (De Pater et al., 2020). The same goes for 9.8 kilometer New York East Side Access extension of the Long Island Rail Road, which was estimated to cost 2.2 billion USD$ and to be finished in 2011. Now, it is projected that the railroad will be finished in 2022 with a total cost of 11.1 billion USD$ (Vartabedian, 2021). In addition, with the hyperloop being a completely new form of infrastructure, it is likely that the first corridor constructions will run into unforeseen problems, resulting in higher capital costs. Over time, when more and more corridors are built and the construction process becomes more familiar, capital costs might decrease. This shows that the capital costs of the hyperloop, just like any infrastructure project of similar dimensions, are of considerable size.

Comparing the costs of hyperloop infrastructure to that of high speed rail or highways is quite difficult, since the capital costs of these projects also differ due to circumstances like project delays, terrain, surroundings and other unforeseen barriers. To take the first example from above, the HSL-Zuid high speed rail line ended up costing 58.4 million EUR€/km (De Pater et al., 2020). The average costs of an elevated 4-way major freeway in the South East of the United States has an average cost of 44.58 million USD$ (Compass, 2022). Even though cars are not always considered as a direct competitor to the hyperloop, it is useful to give perspective on the costs of infrastructure projects in general. When these numbers are compared to the hyperloop capital costs estimations by AECOM and Delft Hyperloop, it can be seen that these costs are in the same order of magnitude, meaning that hyperloop infrastructure capital costs could potentially be similar to that of already established forms of infrastructure. One major difference however between the hyperloop and rail and road is that to be feasible, a hyperloop corridor should be at least 100 kilometers in length. This means that the starting capital costs of a hyperloop corridor will run well into the multiple billions of euros or dollars, while rail and highway projects can be shorter in length to be feasible, resulting in lower starting capital costs.

4.1.3 Operational and Maintenance Costs

The operational and maintenance costs of the hyperloop include:

- Energy consumption pod
- Energy consumption tube and vacuum infrastructure
- Energy consumption stations
- Maintenance equipment
- Part replacement
- Insurance
- Ticketing
- Personnel
  - Maintenance
  - Pod service
  - Control
  - Administration and support
  - Security

At this point in time, there are still many unknown parameters to effectively assess the operational and maintenance costs of the hyperloop, since no operational hyperloop has been built yet. However, some assumptions can be made when comparing the hyperloop to rail and aviation. The energy consumption of the hyperloop is assumed to be less than that of aviation and high speed rail, resulting in less expenses for purchasing electricity when compared to these modes of transport. The lack of friction forces due to the near-vacuum tube environment and levitation system could result in slower wear of the infrastructure than rail infrastructure, cutting costs on maintenance and replacement costs. However, since the infrastructure consists out of many components (tube, track, vacuum pumps, pods etc.), more parts need to maintained or potentially replaced. It is also not clear how easy it would be to replace for example part of the tube when some part of it is damaged. This depends on tube material, the type of damage, their vertical alignment and how large the tube sections will be.

In terms of personnel, the hyperloop will resemble the employee structure of train systems and aviation. Maintenance crews will be similar to that of rail, maintaining large stretches of mostly linear infrastructure. The hyperloop system requires control personnel to ensure smooth operation and potentially helping out during emergencies, similar to air traffic control. The biggest difference is that, since pods will be fully automated, there is no need for personnel like pilots or train engineers. Pods will also have to be cleaned in between trips, similar to airplanes in between flights or trains between trips. Personnel costs of the hyperloop could therefore be similar to those of aviation and rail systems of similar sizes.

Even though it is not clear whether the operational and maintenance costs of the hyperloop will resemble those of rail or aviation, a few examples of the operational and maintenance costs of these types of transportation are given to illustrate the order of magnitude of these costs. The English rail system cost 17.4 billion GBP£to operate in 2020, which at the time was around 19.6 billion EUR€ (Smart Transport, 2021). The rail system totals up to 15,800 kilometers in length, resulting in operational and maintenance costs of 1.2 million EUR€/km railway. Amsterdam Schiphol airport had in 2021 a total of 816 million EUR€ of operating expenses, of which around 20% were security costs, which are also costs to be made by the hyperloop station (Schiphol Group, 2022). Operational costs of the hyperloop are, therefore, also most likely to be in the several hundreds of millions of euros, depending on the size of the network.

4.2 Demand

The demand for the hyperloop, or for any mode of transportation, depends on a number of factors. These include for example the demographics and economics of a city, ticket prices, travel time savings, reliability, comfort and accessibility of the station (Victoria Transport Policy Institute, 2015). These factors also partially determine the position of the hyperloop on the public transport market. The market analysis is discussed in Section 4.4. Some of these factors are characteristics of the city where the station is located, others are characteristics of the hyperloop system, which are discussed more in Chapter 6. It must be mentioned that the demand discussed in this section applies to the hyperloop as transport for people. The demand for the hyperloop as a mode of cargo transport is not taken into account here.

4.2.1 Type of Passenger

Route placement of the hyperloop is essential when looking at demand. The connected cities need to be able to supply the demand needed to make the system feasible, which depends on city population and economics. The type of passenger that travels between connected cities is of importance here. Some people might take the hyperloop for work-related travel such as daily commuting or a business trip. Others might take the hyperloop for social recreational activities, such as leisure trips, visiting family or going to school/university. Each type of traveler values different characteristics of the system. Social recreational travelers for example value ticket prices, daily commuters value ticket prices and reliability, and business travelers value travel time savings. Cities with a large population and a large number of businesses are expected to more easily supply enough passengers of each type to make the hyperloop a feasible mode of transportation than smaller cities and less densely populated areas.

Cities that accommodate large companies or multinationals will likely supply a large number of people that travel daily for business trips or commute. For example, if a multinational has branches in two different cities, it will have a great interest in a fast connection between the two branches to transport people and knowledge. With the travel time reduction that the hyperloop offers compared to high-speed trains and aviation, the hyperloop enables travelers to use the time normally spent traveling for something else. The same interest would hold for companies that have clients based in other cities connected by the hyperloop or for people that can live in one city and work in the next due to more attractive residential areas. For people living in one city and working in the next, the hyperloop could become part of their daily commute. Research shows that one-way daily commuting times are 25 minutes on average in 2019 in Europe, with 26.3% of the working population traveling between 30 and 59 minutes (Eurostat, 2020). This number has also grown over the years, with average commuting times in the United States increasing by 10% between 2006 and 2019 (United States Census Bureau, 2021). With the short travel times that the hyperloop offers, such as an approximately 30 minute trip from Amsterdam to Paris, the hyperloop could become part of people's daily commute. This would also depend on system characteristics such as ticket pricing and accessibility of the stations within or near the city, but this data shows that people are willing to travel long enough to potentially use the hyperloop in their daily commute, since its travel times fit into the time people are willing to spend on commuting every day.

Demand could also come from the leisure sector. This type of traveler often values ticket prices and comfort, which means that the fast travel times of the hyperloop do not play as big of a role as for business travelers. If ticket prices are to compete with those of aviation, the hyperloop could become a travel solution for leisure travelers. However, since the hyperloop moves along fixed routes, the potential holiday destinations reachable by the hyperloop are limited. Since the hyperloop network will most likely be continental and connecting larger cities, the hyperloop could be a good solution for city trips, but far away holiday destinations using the hyperloop will not be possible without using other modes of transportation as well.

4.2.2 Number of Passengers

It is very difficult to estimate the number of passengers that will use a certain hyperloop corridor on a daily or yearly basis. This again depends on the city and system characteristics described above. However, it can be useful to look at the number of passengers that use competitors of the hyperloop and the expected growth in demand for these modes of transportation.

With operational distances between 100 and 1500 kilometers, the hyperloop competes with trains, airplanes and cars. The hyperloop is therefore expected to take over some of the passengers that are currently traveling with these modes of transportation due to user benefits. Another reason people might prefer to use the hyperloop over other modes of transportation is the sustainability trend that the world is currently in (European Investment Bank, n.d.). More and more people choose sustainable modes of transportation over fossil fuel based modes of transportation. An example of this trend is 'flight shame', a social movement which encourages people to fly less due to the carbon emissions by the aviation industry. Higher taxes on fossil fuels and plane tickets could also make cars and aviation more and more expensive, forcing people to use alternative solutions such as the hyperloop. The hyperloop could potentially also create new travelers by giving people the opportunity to work and/or live in different places due to fast connections.

A common misconception about the hyperloop is that the hyperloop will completely replace aviation or high speed rail. With the characteristics of the system, this is not possible. It is not likely that every city in Europe or on other continents will be connected by a hyperloop network, since the infrastructure is fixed and expensive. This is also the reason why the hyperloop is not expected to be used for intercontinental travel, since crossing oceans with a tube network is an extremely big challenge. It is more likely that the hyperloop will complement other types of transport. People could fly intercontinental, use the hyperloop to move from metropolis to metropolis and take the train to reach smaller cities. With the demand for travel predicted to almost triple by 2050 (Gössling and Humpe, 2020), it will also be hard for aviation and rail to provide enough capacity for the demand. Aviation is already predicted to face capacity challenges (Supporting European Aviation, 2018). The hyperloop could take over part of this demand and provide more capacity to enable this growth.

4.3 Revenues

To measure the expected success of a hyperloop connection, it is useful to look at the expected revenues that will be generated by it. The most obvious revenue will come from selling tickets. Other revenue can come from the hyperloop station. These two sources of revenue will be discussed in this section.

4.3.1 Tickets

Selling tickets for seats on pods will be the main way to generate revenue using the hyperloop. The money earned from selling tickets will first be used to pay back the capital investments, pay for operational and maintenance costs and, in a later stage, potentially return profit. Tickets need to be priced such that the investment is returned in a suitable amount of time (return on investment, ROI) while also competing with prices of competing modes of transportation like high speed rail and aviation.

At this current point in time, it is difficult to put a precise price tag on a hyperloop ticket. This depends on the capital costs, operational and maintenance costs, ROI and demand. In the early stages of hyperloop operation, mainly early adopters will be buying tickets. These passengers are willing to pay more to be the first ones to use the hyperloop, which means tickets can be priced higher (Kenton, 2021). Once the hyperloop has shown its value, demand can grow and tickets can be priced lower to attract more users.

Ticket prices can also be adjusted to the fluctuations in daily demand due to rush hour traveling in the morning and evening. Similar to other modes of transportation, tickets can be priced higher during rush hour since the demand is higher, but also to force people to use the system at less busy moments to prevent capacity issues.

Depending on the financing and ownership structure of the hyperloop system, tickets could potentially be subsidized by national or international governments, making them cheaper to, for example, push travelers to use the hyperloop instead of airplanes to reduce emissions. Government financial aid can also be used to help the hyperloop be competitive with other modes of transportation in the first years after implementation to get demand up to speed.

4.3.2 Station

Another source of revenue is the hyperloop station. Airports are earning increasingly more money through non-aeronautical revenue, like concession sales such as food, beverages and retail, but also parking spaces around the airport and offering office spaces and hotels for people to conduct business (Florida Tech, n.d.). In 2017, non-aeronautical revenue accounted for 39.9% of global airport revenue (Airports Counsil International, 2017). These sources of revenue could also be applied to hyperloop stations. However, there are some key differences between airports and hyperloop stations. The first is the amount of time people spend at the hyperloop station compared to airports. Due to the extensive security measures at airports, passengers often arrive at the airport a few hours before their flight, meaning they have substantial time to kill if the security and check-in procedures run smoothly. This time is often used to shop or consume food or beverages, generating revenue for the airport. Since the hyperloop is meant to operate as a turn-up and go system, passengers are meant to spend less time at the station, therefore spending less money at shops, restaurants or kiosks. Even though hyperloop stations will also feature security measures, hyperloop pods will depart more frequently than airplanes at airports. So if a passenger misses a desired pod due to for example busy lines at the security section, a next pod to their destination will most likely depart in just several tens of minutes. The second difference between hyperloop stations and airports is their placement. Hyperloop stations could potentially be placed closer to the city than airports, making them more accessible by other modes of public transport, reducing the number of people that travel to the hyperloop station by car and therefore increasing the number of parking space needed. Building closer to cities does mean that there could be less room for large parking spaces, limiting the number of parked cars and therefore the parking fees compared to airports. These sources of revenue will therefore potentially be lower than that of airports, but they still generate some revenue for the hyperloop station's owner.

4.4 Market Analysis

In this section, the market position of the hyperloop is analyzed. The hyperloop is placed in perspective to other modes of public transport to find its strengths and weaknesses and to find its biggest competitors in other modes. First, a few criteria are identified that make modes of transportation successful and attractive to users. Then the public transport market is divided into regions of travel distance where different modes operate. These regions make it easier to compare different modes of transportation and find competitors of the hyperloop per target region.

4.4.1 Criteria for transport services

There are seven criteria that make public transport attractive to its users. These criteria are accessibility, timeliness (being on demand), directness, speed, comfort, safety and cost. For public transport to be successful, future modes definitely need to meet all of these criteria (Humphreys, 2016). The first three of these criteria can be put under convenience. Mainly for relatively short distances, convenience is a very important factor for public transport users. The pick-up point should be nearby and easily accessible, the transport should be mostly on demand and ready when needed and the transport should be as direct as possible, bringing the passenger from origin to destination with minimal detours and transfers. For speed, not the operational speed should be taken into account, but rather the total time the transport takes to bring the user to the destination. This includes waiting times and transfer times. Comfort is a factor that becomes more and more important the longer the trip takes. It is related to the space per person on the vehicle, crowdedness, services and facilities on board. This criterion has more impact on longer distance travel. Safety is a factor that lies close to comfort in terms of perceived safety and security. In principle, of course, every mode of public transportation should be safe and this is more of a requirement than a criterion. However, there can be a distinct difference in safety per mode of transportation. The chances of a deadly incident are far higher in a car than for example in a train (van Essen et al., 2019). Next to this, the feeling of safety and security inside a vehicle will add to the level of comfort in traveling and the overall positive experience of the passenger. The last criterion is the one that mostly speaks for itself. The cheaper the transport, the better. Still, how important this factor is deemed, can highly depend on the distance that is traveled with the concerning mode of transportation and also on the other criteria that are at play. If public transport is very convenient and fast, people are willing to spend just a bit more.

4.4.2 Transport per distance region

To find out where the hyperloop will stand in the public transport market and how it will score on the mentioned criteria, it is easiest to place it in perspective with other modes of transportation in terms of distance. If two modes of transportation share the same operating distances, they are likely to share the same market of demand. Therefore, different modes of transportation will be divided based on the travel distance they cover. Five regions of travel distance can be identified. It should be noted that these distance regions are highly dependent on the location. For example, suburban distances can be much larger in the United States or in Asia than in Europe. The distances in this report are based on Europe.

The first distance region is the terrain of urban transport, that covers distances inside a city, so up to 20 km. The existing transports that can be thought of for these distances are trams, buses and metros, besides of course personal transport such as walking, cycling or going by car. Moving into the second distance region, there are suburban distances of 20 to 60 km. Transport modes that move both in urban and suburban environments are metros, buses and cars. A transport choice that is added when moving to suburban distances is regular rail. This is not considered urban transport, since most railway lines have one or at most a few stations per city. Regular rail becomes a big player when moving in between cities. For regional transport, the third distance region that covers 60 to 150 km, only cars, buses and regular rail are considered. For the higher end of these distances, another mode of transportation can be added: the HSR. This kind of rail transport is faster than regular rail and only used to cover larger distances at a time. These last four modes of transportation are all able to cover the next region of distance, which is national distances of up to 600 km. This number is very dependent on the concerning country, so this number may be seen as an estimation of the average for Europe. The last distance region contains the international distances within Europe of more than 600 km. Most of these trips are done by plane. Looking even further to intercontinental distances, these are only covered by air passenger transport. The hyperloop, as it is proposed now cannot operate intercontinental, first of all, because the distances are too big, making investment costs of the infrastructure impossible to cover. Secondly, most continents are separated by large bodies of water and there have not been any good proposes yet for the hyperloop to cross oceans.

As was found in section 2.4, the ideal operational distances of the hyperloop is between 100 and 1500 km. As a mode of transportation, this would put the hyperloop in the higher part of the regional distances and in national and international. Figure 4.4.1 shows a distance chart with all the modes of (public) transport in their corresponding regions.

4.4.3 Market positions

Dividing types of transport based on their typical travel distances, gives the opportunity to compare competing modes of transportation. Different transport services that cover the same distance regions will serve the same market of users. Their position will therefore depend on how well they score on the 7 criteria of public transport. The importance of the criteria depends on the distance region that is considered. For example, for long distances, comfort is more important and for short, urban distances the accessibility and directness are more important. In Figure 4.4.1 it can be seen that the hyperloop

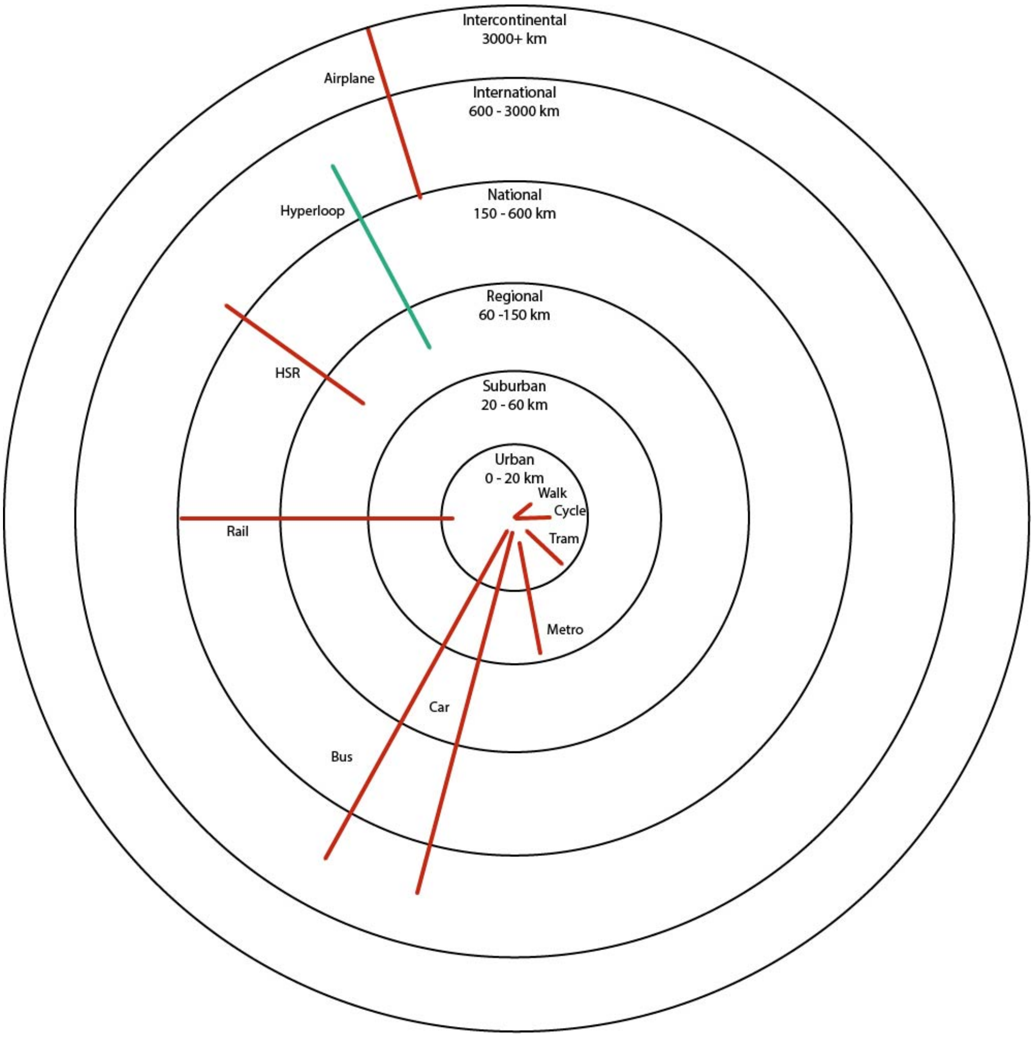

Figure 4.4.1: Modes of transportation and the corresponding distances on which they typically operate. The hyperloop has been indicated in green.

competes in distance region with the car, the bus, regular rail, HSR and air passenger transport. The hyperloop will be compared with its competitors on all 7 criteria for each distance region.

Long regional and national distances

For both the longer regional distances and the national distances, the hyperloop can be compared with regular rail, HSR, cars and buses. Looking first at the convenience criteria, it may be noted that the car as a personal mode of transportation is the most convenient. The car scores well on accessibility, as car owners usually have a car close to their residence, on directness, as most destinations are well reachable by car, and on timeliness as a personal transportation can be taken at any moment. For the the comparison of the hyperloop to its competitors, the car will further be left out, as it is more a personal mode of transportation than a public transport and, therefore, hard to compare.

All other modes of transportation for these distances have fixed stations in a city or other inhabited area. Therefore, people that do not live in the concerning area, first have to travel a bit to reach a station. This results in an overall lower score in accessibility for track bound modes of transportation. However there is a difference, of course. Regular rail makes relative frequent stops and therefore has more stations per area than HSR and the hyperloop. Buses for long regional and national distances have a stop frequency that is comparable to regional trains, with more stops in populated areas and few to none in between. Having more stations where people can board, gives a higher probability of a station being close to people's home. This results in a higher score on accessibility. As the hyperloop becomes more efficient for larger distances (up to a maximum), it is expected that the hyperloop has few stops. For a European network, it would be one station per country, maybe more for larger countries. HSR also has fewer stops, but looking at current high speed lines in European countries, it is concluded that these have more stops than what is expected for the hyperloop. So, with the same reasoning as for regular rail, HSR scores better on accessibility than the hyperloop.

The directness of a track bound transport service is also lower than transport modes that have more ubiquitous infrastructure such as buses and cars. Very similar to accessibility, the directness of a mode of transportation that is bound to stations or predetermined stops is very dependent on where the stations are and how many stations there are. If a mode of transportation has lots of stations it can reach, the chances are higher that the service can bring you directly to your desired destination. The ranking of regular rail, HSR and the hyperloop on directness will be the same as accessibility.

Timeliness will likely create an opportunity for the hyperloop. With the high frequency at which pods can travel through the tubes, chances are high that there is always a pod leaving at the time you need one. For every transportation service it is most efficient for a vehicle to be filled with passengers to its maximum capacity. For a regular train or HSR, it can take some time to collect enough people that want to go to the same destination to fill up a vehicle. Individual hyperloop pods are much smaller than entire trains. Therefore it is also easier to collect enough demand for a destination to fill up a pod. This also contributes to more frequent departures to the same destination of the hyperloop, making it score well on timeliness.

For the speed criterion, there needs to be a very clear distinction in travel distance. Compared to all four of the other long regional and national transport services, the hyperloop has the largest cruising speed. After that comes the HSR and lastly cars, buses and regular rail with comparable speeds. The hyperloop is super fast, but, as it needs to speed up and slow down gradually to ensure a comfortable trip, this high speed will only be reached on longer tracks. Looking at the lower bound of 100 km distance, the average time this takes the HSR and the hyperloop can be compared. For the maximum speed of the HSR, 350 km/h is taken. This speed can be reached by HSR trains in Europe. The maximum speed of the hyperloop is 1000 km/h. Assuming that both use the same acceleration rate, it will take the HSR only 5 km to reach cruising speed. The hyperloop needs 40 km. Calculating with these acceleration and deceleration trajectories how long each transportation mode takes to cover 100 km, it is found that the hyperloop does it in 11 minutes and the HSR in 19 minutes. So for this shortest distance, even though the hyperloop travels at cruising speed for only a small part, it is already 63% faster than the HSR. This means that for all longer distances up to international, the hyperloop will become increasingly faster for longer distances compared to other modes.

The level of comfort of a transportation service is determined by the space per person, crowdedness, services and facilities on board. The inside of a hyperloop pod is designed to look like a first class train compartment in terms of seats and personal space. Next to that, a spot inside a hyperloop pod needs to be booked in advance. For safety reasons, it is impossible for a pod to be overbooked, as it is mandatory for passengers to be seated during acceleration and deceleration, just as in a plane. It should be noted here that for longer distances most other modes also work with bookings. Only regular trains and buses on regional and short national distances have a risk of becoming too crowded. With regard to services and facilities on board, it must be noted that the hyperloop pod is a relatively small, autonomous vehicle. Therefore, the services and facilities on board will be automated and confined to the passenger's seat. It will, for example, not have a restaurant area as a train might. The pod will feature a restroom.

The safety of the hyperloop will be compared with general road transport (e.g. cars, buses) and rail transport. The most common cause for road accidents is human error (Perchonok, 1972; U.S. Department of Transportation, 2018). For the cause of rail accidents human errors, technical failure and external intrusions are equally important ("Railroad Accidents: Common Causes, Statistics and Prevention", n.d.; Kim and Yoon, 2013). As the hyperloop only works with automated vehicles, the room for human errors is drastically reduced. The closed off environment of the tubes now provides another advantage next to reducing air resistance. With the hyperloop pods traveling through tubes, the possibility of external intrusion is also strongly reduced. However, since no full scaled hyperloop system has been built, it is hard to really assess the safety of the system. What could be said, is that the safety of the hyperloop will for the largest part depend on the technical resilience. And, it may be expected for a new mode of transportation that it should be at least as safe as the safest existing mode of transportation, which is the airplane (in fatalities per passenger kilometer; European Union Agency for Railways, 2017).

The cost of a hyperloop ticket is still something that is hard to predict. The ticket price depends on the investment costs of the infrastructure, operational costs and how fast the investor want to earn it back. It depends on possible subsidies of governments, on the target group and the demand per time of the day.

International distances

For international distance travel of up to 1500 km, the air passenger transport is added to the options. For these distances, cost and comfort are very important, since usually a longer time needs to be spent inside the vehicle.

First, for comfort, the biggest difference between the hyperloop and an airplane is the crew on board an airplane. On every airplane there is a crew that can provide service in the form of selling food and beverage, and, more importantly, directions and support in case of an emergency situation. The role an on board crew plays in the actual safety, will be discussed later. In absence of an emergency situation, an on board crew will add to the perceived safety of the vehicle. However, considering the way that planes are designed now, the space per person may be expected to be bigger inside the hyperloop pod. It may also be noted that the flights with which the hyperloop aims to compete, are the often cheap, relatively short continental flights. Elaborate on-board service on these flights is less common than on long intercontinental flights. The hyperloop cannot compete with these longer flights based on the travel distance.

The placement of airports and hyperloop stations results in a large difference in convenience between the two modes of transportation. Since airports require a lot of space for runways, they are usually located far away from the city center. In comparison, hyperloop stations take up much less space and could therefore be placed on more central locations. This means that the hyperloop would likely score better on accessibility and directness than air passenger transport.

For speed it may first be noted that the hyperloop and the airplane have comparable cruising speeds. However, airport security and logistics require the passengers to be present long before the departure of the flight. This waiting time must be added to the total travel time of the air passenger transport. As the hyperloop is also an international transportation service, it should be able to provide the same level of security as air passenger transport. Nevertheless, with the turn-up-book-and-go concept of the hyperloop, security procedures in the station should be fast and efficient to not detract from the concept. Faster security checks can be achieved by scanning passengers and luggage simultaneously and by employing face recognition algorithms (Campillo, 2022; Glusac, 2021). If the present day waiting time at the airport is included, the hyperloop and plane will only become comparable in speed after large distance. On a larger distance, the waiting time at the airport will represent a smaller portion of the total travel time. Also for longer flights, airplanes are able to reach higher altitudes where it is possible to have higher speeds. The distance point where the efficiency of planes and their travel time becomes comparable to that of the hyperloop is around 1500 km (Federici et al., 2009). Therefore, this distance is seen as the maximum at which the hyperloop could have a good position on the transport market.

It may be expected that the safety of airplanes and hyperloop pods would be comparable. Both are pressurized vehicles moving through a low pressure environment. In case of an emergency, for both transport services it can be hard to evacuate the vehicle quickly, since airplanes move several kilometers above the surface of the earth and hyperloop pods first need to slow down and find a safe haven with evacuation airlock doors. The human factor in these modes of transportation is a huge difference. In case of an emergency or passenger injury or illness on board of a plane, there is a trained crew to support and provide first aid. On the other hand, because airplanes are still partially piloted by people, there is a probability of accidents caused by human errors. The hyperloop pod is unmanned and therefore human factors are largely reduced to communication errors from schedules or the control room. However, on the hyperloop pod, the emergency response will need to be automated and initiated by the pod itself. For example, in case of a passenger injury or illness, first aid protocols would be communicated through the pod's systems and need to be carried out the passengers. The safety of the hyperloop will thus be very dependent on technology and will have to undergo lots of tests and proofs of concept before being deployed.

As has been established in the last section, the ticket prices of the hyperloop are still unknown and hard to predict. What is commonly known, is that airplane tickets can be very cheap. This has multiple reasons. First of all, a lot of airlines get subsidies from governments. Next to that, the fuel of airplanes, kerosene, is not taxed and in most countries, airplane tickets are not taxed as well. Lastly, airlines experience a lot of competition in their own branch and therefore lower their ticket prices by saving on service to compete with others (Koster, n.d.). If taxes on flying would be higher, ground-based transports such as the hyperloop and the HSR would be able to compete a bit better in prices. However, it must still be noted that the infrastructure of trains and the hyperloop will still be a large source of investment and maintenance cost, whereas the infrastructure for airplanes is very small (Koornstra, 2021). So even if the taxes would be the same, the infrastructure of ground based transport is a large cost generator, that is likely to be reflected in the ticket price.

To give an overview of the hyperloop's expected position on the passenger transport market, relative scores on the seven public transport criteria for all transport modes in the regional, national and international distances, are given in Table 4.4.1. For each distance region, either regular rail or HSR is taken as standard public transport, meaning that their column is put to zero. The other modes of transportation are graded relative to those. Note that these scores are rough estimations, based on assumptions, not on real data. The table is merely meant to give an idea.

Table 4.4.1: Overview of the relative scores on public transport criteria of different modes of transportation for regional, national and international distances.

	Regional					**National**					**International**				
	Car	Bus	Rail	HSR	Hyperloop	Car	Bus	Rail	HSR	Hyperloop	Car	Bus	HSR	Hyperloop	Airplane
Accessibility	+	0	0	-	-	+	0	0	-	-	+	0	0	0	-
Timeliness	+	0	0	-	+	+	0	0	-	+	+	-	0	+	0
Directness	+	0	0	-	-	+	0	0	-	-	+	0	0	0	-
Speed	0	0	0	0	0	0	-	0	+	++	-	-	0	+	+
Comfort	++	-	0	+	+	+	-	0	+	+	+	-	0	0	0
Safety	-	-	0	0	+	-	-	0	0	+	-	-	0	+	+
Cost	+	0	0	-	TBD	+	+	0	-	TBD	-	+	0	TBD	+

4.5 Multi-use of Infrastructure

With the implementation of the hyperloop, a whole new infrastructure needs to be built of kilometers in length linking even international areas. Apart from using this enormous network of tubes to propel the hyperloop pods in, there is also an opportunity to use the infrastructure for extra purposes. Effective multi-use of the infrastructure might also help with financing part of the project and could be interesting for a business case. In this section, some of the possible multi-uses of the hyperloop infrastructure are explored.

If the vacuum tubes were to be above ground, either on pillars or level with the floor, the surface on top of the tubes is free for other purposes. The most discussed and most promising purpose for this area is to cover the top of the tube with solar panels. The generated photo voltaic power can be used to partly provide the hyperloop infrastructure with energy. This way of using the own infrastructure space for power generation can save the hyperloop system in costs for energy provision. Covering the top of the tube with solar panels would increase capital costs.

The linear electromagnetic motor of the hyperloop enables regenerative braking, where energy of the moving pod can be returned to the track during braking. This principle of recirculating energy from the pod to the track gives rise to the idea of using the track as a giant power storage unit. Part of the energy could thus be stored in the moving pods, returning it to the track when braking happens. The power storage could also be expanded with capacitors or magnetic superconductors that are integrated in the footprint of the infrastructure to make effective use of land. Using the hyperloop tracks as power storage can relieve overloaded power grids and add to the resilience of the energy network of a country.

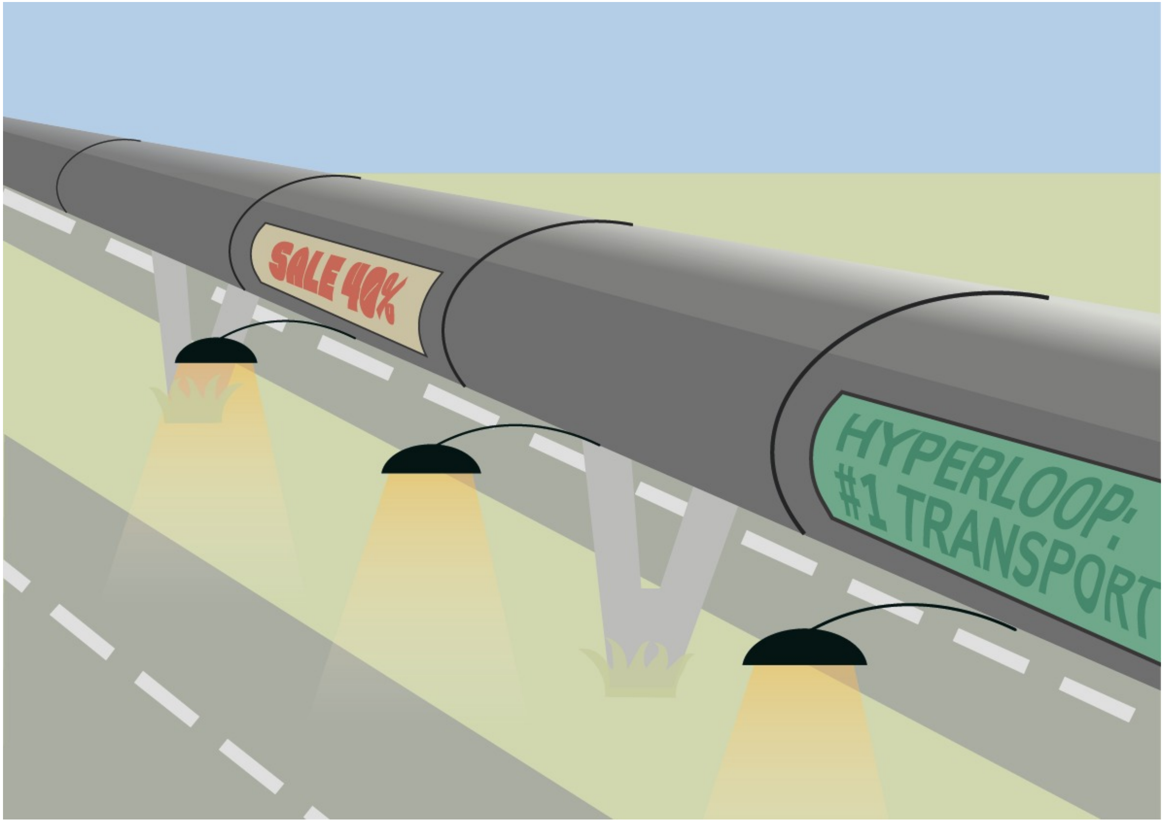

Figure 4.5.1: Sketch of a multi-used hyperloop tube along a road. The street lighting and some advertisements are integrated into the hyperloop tube.

Placing the thousands of kilometers of hyperloop tubes calls for the acquisition of a lot of land. As this could be a hard task involving a lot of different parties, there have been proposals to place the hyperloop infrastructure alongside existing infrastructures such as highways or railways. The hyperloop tubes could be placed next to train tracks or above them on a construction of pillars. When the hyperloop tubes run alongside highways, they could be put on pillars that are placed in the center reservation. With the hyperloop infrastructure above or besides other infrastructure, street lights or signaling could be integrated into the tubes to reduce extra materials in the infrastructure. This type of multi-use of the infrastructure can be seen more as the utilization of an opportunity than a lucrative extra. Another use of the tubes along existing infrastructure that could be lucrative, is to sell billboard space. As for the hyperloop, the only function of the tube is to preserve the low-pressure environment, the outside appearance of the tubes can be anything. When placed alongside existing infrastructure, there is a large number of people that see the outside of the tubes. This would give the tubes a potential use to be sold as advertisement space. A sketch of this type of multi-use along other infrastructure is given in Figure 4.5.1.

The idea that the hyperloop could follow existing infrastructure, such as highways, comes with an important note. If the hyperloop tubes would be above the highway at, for example, the height of a regular overpass, this is certain to interfere with overpasses at highway junctions. Thus, placing the tubes above highways might not be ideal, as it would require a lot of planning and possible redesign of junction structures, which will be costly. Another possible issue with placing hyperloop tubes along existing infrastructure is the curves. As the hyperloop moves with high speeds, the turns in tubes have a minimal radius, as was found in Section 2.4. Slower modes of transportation, such as road and rail, can take sharper turns. Therefore it will not always be suitable for the hyperloop to follow existing infrastructures.

Another option of alignment of the hyperloop tubes would be to put them underground in tunnels. As a hyperloop corridor requires two tubes, departure and arrival, and tunnels are optimally round, placing both tubes in one tunnel leaves additional space for other utilities (Delft Hyperloop V, 2021b). Tunnels for hyperloop tubes could then be combined with other tube transport, for example for goods. The tunnels in more urban areas could be combined with for example sewers or rainwater reservoirs. Also, the space could be used to accommodate wiring for power and communication. A sketch of a multi-used hyperloop tunnel is given in Figure 4.5.2. However, putting both hyperloop tubes in one tunnel, instead of two separate, smaller tunnels, would require the excavation of a tunnel with twice the diameter of a single tube tunnel. The volume that needs to be excavated for this large tunnel would then be 4 times as large. Considering that excavation costs contribute up to 80% to the total construction costs of a tunnel ("Annex 13 - Case study on tunnels", n.d.), choosing for a larger tunnel diameter would dramatically increase the construction costs.

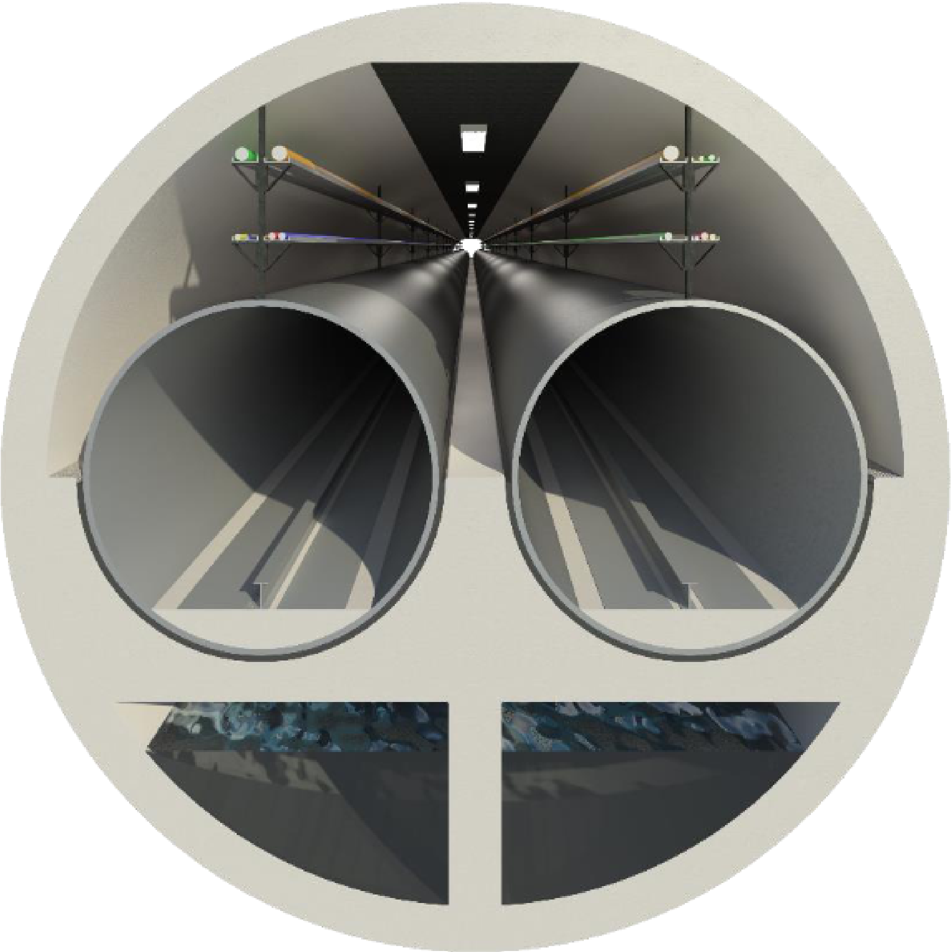

Figure 4.5.2: Hyperloop tunnel that includes different utilities such as water, power cables or internet cables (Delft Hyperloop V, 2021b).

Chapter 5

Barriers in Hyperloop Development and Implementation

With companies and student teams around the world working on hyperloop technology, and large parties investing in this development, hyperloop technology and knowledge is improving rapidly. However, there are still many barriers to overcome before the first commercial hyperloop can be implemented in Europe. Even though there have not yet been any tests of a hyperloop system moving at the promised 1000 km/h, it is not expected that the largest barriers are at the technological front. Since the hyperloop is a drastically new and even disruptive mode of transportation, most barriers for its final development and implementation will likely be found in regulatory, administrative and governmental issues. Some of these barriers have already been touched upon in Chapters 3 and 4 about the hyperloop stakeholders and its business case. To eventually implement a hyperloop network, solving these barriers is of utmost importance, together with finding the right stakeholders and having a convincing business case. Therefore, in this chapter the barriers that the implementation of the hyperloop still faces on the non-technical side, are separately investigated and discussed. Ideas in this chapter were established thanks to discussions with experts from TNO, the TU Delft faculty of Technology, Policy and Management, TBI and the Dutch Ministry of Infrastructure and Water Management and Ministry of Economic Affairs and Climate Policy.

5.1 Standardization

The first barrier that the further development and implementation of the hyperloop faces, is standardization. For every mode of transportation, and especially an international one such as the hyperloop, it is important that the system is standardized. Standardization should be applied on several areas. First of all, the hyperloop techniques need an international, or at least European standard. Currently, there are multiple hyperloop companies active in Europe that independently develop their optimal hyperloop system. If a European network is to be realized, a decision needs to be made to go with one system. If not, it may happen that pods that can travel in one country, are not compatible with the tubes that lie on the other side of the border. This would heavily impact the efficiency of the hyperloop network. Since no plans are in place yet to build commercial tracks in Europe, the hyperloop creates the opportunity to first decide on a standard and then implement a network that works seamlessly in all connected countries. Making a decision however, is far from easy. For example, opting for one standard type of propulsion system, would limit innovation in this field of the hyperloop.

Having an external party to set a standard in the technology is probably not the way to go, but there is another option. If there would be a European Hyperloop Agency to initiate the implementation of a hyperloop network, as was introduced in Section 3.4.1, they could play a role in the standardization of the system in another way. In the EU there are different safety agencies for modes of transportation that develops safety standards and requirements for transport in the EU, such as for example the ERA that guards the safety standards for European railways (European Commission, n.d.). A European Hyperloop Agency could also assign an independent safety agency to fulfill this task for the European hyperloop. This authority would set and guard safety standards for the hyperloop, making the first step towards the implementation of a standardized hyperloop. When the safety standards are set, they can be published. It is then up to the market, to the hyperloop companies, to make sure their technology lives up to the safety standards. The best system can then be set as the standard for the European network.

With the safety standards, there is also a need for standardized operations of the hyperloop. For the hyperloop to be one consistent transport network, it is important that the procedures and operations in the station are the same, regardless of in which country they enter the hyperloop network. Every station should have the same level of security and service.

5.2 Borders and permits

If the implementation of a European hyperloop network would be successfully initiated on a European level, the next barriers will be found in the countries through which the tubes would have to go. Here, the individual national governments need to coordinate the construction of the tube infrastructure. For this, the European initiator needs to get all national governments on board of the European network. In doing this, the initiator will likely stumble on barriers between different countries of the network but also on barriers within individual countries. All these barriers have largely to do with legislation, spatial planning and politics.

5.2.1 Barriers between connected countries

When placing infrastructure in different countries, the main barrier is the different authorities that govern over their own part of the infrastructure. In cross border projects there are usually two or more national governments involved, several local governments, but also different environmental and health legislation, different private contractors, suppliers, end users. All these different stakeholders have a probability of forming issues at one point, which could slow down or stall the whole project (Garemo et al., 2015).

Different countries have different structures in organization and authority of national, regional and local governments. These different governmental structures can lead to large differences in how long it takes for legislation and permits to be in place in order to make the construction of infrastructure possible. A good example of this is the "Betuwelijn", a cargo rail connection that is supposed to run between the Rotterdam harbor and Oberhausen in Germany. In this case, the Dutch part of the route has already been finished. However, the railway cannot be used to its full potential, because for the German part, not all necessary permits are granted yet (NOS nieuws, 2017; Niewold, 2019).

5.2.2 Barriers within connected countries

Before tubes can be placed within one country, still a lot of obstacles need to be overcome. Even if there already are international designs, regulations and safety standards, and neighboring countries are on board, more national and local issues will need to be solved.

As the hyperloop is a transport system that covers large distances at a time, it would likely have only a few stations per country, in larger cities. However, the tube infrastructure will need to be placed straight through the rest of the country. This might lead to resistance from regions that have to accommodate the tubes, but do not enjoy the benefits of a station. Resistance from local authorities would certainly slow down the implementation of the network. Also, without significant resistance from the local governments, the national government could have its own reservations about implementing a fast network that only connects already prosperous parts of the country with the rest of the continent, but does hardly anything for other regions.

Another significant barrier for the implementation of a new transportation network, especially in European countries, is space. Most countries are already very crowded and finding enough space for the hyperloop infrastructure can be hard considering existing infrastructure, buildings and natural relief. The fast character of the hyperloop system makes it particularly hard to fit into the landscape, as the high speed does not allow for sharp turns. The infrastructure needs to consist of mostly straight lines, that also do not vary too much in height. The construction could therefore become very expensive or lead to the deconstruction of other infrastructure, which might leave a government hesitant to pull through.

The last barrier within a connected country that is discussed, has to do with the country's politics and government plans. As was found in Section 3.4.1, it will be very hard to implement the hyperloop infrastructure without the help of the national government. Most countries in Europe are democracies, so a plan for a new infrastructure needs to first be independently investigated, approved and added to the multiple-year plan before it can be executed. Usually this process depends on elaborate procedures and can be time consuming. And that is even after the national government decides to put effort in investigating the possible implementation of a new infrastructure. It is not certain if all countries that would be connected to the European hyperloop network, would see the benefit of this. A nation could for example just have invested in a high speed rail network and might not have the financial resources for an even faster network or see the urgency of it. Other governments might have other reasons not to be interested in the hyperloop. A barrier can therefore be found in the need to find sufficient drivers for governments to be willing to participate in the development and implementation of the hyperloop.

5.3 Financing

Maybe the largest barrier of the implementation of a hyperloop network is the enormous investment it requires. Even if the cost per kilometer is not much higher than other modes of transportation, for the hyperloop to operate at its full potential, hundreds of kilometers of infrastructure are needed. Next to it being a large investment, the hyperloop infrastructure is also a high-risk investment, since infrastructure projects almost always tend to exceed the calculated budget (van Wee, 2004; Day and Harvey-Rice, n.d.; Garemo et al., 2015). There are no parties, neither private nor public that like to take that large of a risk. Public parties tend to avoid risky investments, since they are paying with either loaned money or taxpayers' money. Private parties risk bankruptcy when investing large amounts of money. Also, with the large investment that the hyperloop infrastructure requires, it might take a long time to earn that back with revenues from the system, as ticket prices should be affordable to create demand for the hyperloop system. Making the hyperloop system profitable nevertheless is a barrier that will probably need to be solved by public and private parties together.

Chapter 6

External Effects and Social Merit

While generating revenue is the biggest driver for private parties to invest in the hyperloop, public parties might see positive social effects as reasons to invest in the hyperloop. In some cases, projects with a negative business might still be executed for the positive external effects they cause. Public shareholders are generally willing to invest in large infrastructure projects if the implementation of it generates some form of public merit. Governments for example might invest in the hyperloop if it can be shown that a hyperloop connection will increase wealth and economic prosperity for its inhabitants, or if it has very positive environmental effects.

To assess the external effects and social merit of a hyperloop, assumptions are made on the influence the characteristics of the hyperloop system have on these effects. These effects include social effects like employment and migration, the safety of the hyperloop system, the user benefits that the hyperloop offers and the environmental and spatial effects of hyperloop infrastructure construction and operation.

For making the best estimations of the external effects that the hyperloop would have on society, information for this chapter has been gathered in two ways. Part of the information was found in reports of the effects of comparable modes of transportation, such as railway connections. Additionally, information in the Sections 6.1, 6.3, 6.4 and 6.5 was established thanks to conversations with experts from TNO and from the TU Delft faculty of Technology, Policy and Management.

6.1 Social Effects

The implementation of a hyperloop corridor between two European cities means an improvement in the connectivity between the cities in terms of speed. A better connection will likely have an effect on the surrounding society. In this section the different social effects that could be linked to the implementation of a hyperloop corridor are investigated.

6.1.1 Employment

When a new hyperloop corridor is implemented, first the entire infrastructure needs to be designed and built. The design and construction of the tube infrastructure will temporarily create jobs in R&D, manufacturing and construction. New jobs that could be of a more permanent nature are in operations and maintenance of the hyperloop service (Ricci, 2021).

Important to note here is that these new job opportunities might not necessarily attract people that were unemployed before. It is more likely, because of the mostly specialized nature of the type of jobs that are created, that the people attracted to the jobs are being pulled away from other sectors. In this case, the generation of new jobs is not necessarily a positive effect, as it cannot be said with certainty that it will solve unemployment. A predominantly positive effect might be found on the R&D side of the directly generated jobs. As the hyperloop uses many new technologies and solutions, the R&D will likely have spillover effects in terms of extra knowledge and application of new technologies in other sectors. It may be concluded that it is still unclear if the direct effect of the implementation of the hyperloop on employment is positive or negative. This will need to be investigated further for a specific corridor.

The improved connectivity that the hyperloop provides might also have a more indirect effect on jobs. For the same travel time, people living in the neighborhood of the hyperloop station have a much larger choice in jobs. They can search in their own direct surrounding or in the neighborhood of the city that is connected via the hyperloop. It can be said that connectivity has a direct effect on people's choice in jobs. At the same time, on the other side, the improved connection will give companies a larger pool to find employees. This will have the benefit that it will be easier for employers to find the right person for the job. However, there is also a downside to be noted here. If companies have a larger choice in employees, the people that normally would qualify for a job, might experience crowding-out effects. Whereas people that have better qualifications, may be pulled away from other positions. Thus, also the indirect effect of the hyperloop on employment should be studied case-by-case and for a specific corridor, before it can be decided if the effects are mostly positive or negative.

6.1.2 Migration

In general, a place that has a good connection to other areas, such as a hyperloop station, will attract facilities. The better the connection, the more facilities will move to the station. This can be compared with a regional train station that might have a little kiosk and a large central station or airport that has multiple stores and restaurants. Apart from these commercial facilities, a good connection will also attract companies. For companies, the connection is important for the exchange of information and knowledge. With the facilities and companies, jobs will be created in the area of the station, attracting people to also move closer to the hyperloop station. This statement, however, needs some careful consideration. The discussion if employment is followed by housing or the other way around has been undecided for several years (Bruinsma et al., 2002, Raspe, 2014). Therefore, it cannot be concluded that, wherever the hyperloop station will be built, companies and people will migrate to it. A good connection does not necessarily mean a good economic environment. The hyperloop has a better chance to become a success as an additional connection between two already developed, large cities or business centers.

Looking at migration as an effect of the implementation of the hyperloop, this will most likely be about people and companies that benefit specifically from the fast interurban connection. But as the hyperloop will likely be built in large cities, most companies that benefit from this connection will already be near the hyperloop station. The effect that the hyperloop will have on migration can be likely seen as displacement effects (Van Maarseveen and Romijn, 2015). People that live near the city they work in, can now choose to move to the connected city, while keeping their job.

6.1.3 Housing and Urbanization

A better, faster connection between two urban areas will have an impact on the direct surroundings of the stations. It has been empirically shown that the prices of housing and office spaces near stations are higher than the prices of accommodation farther away (Van Maarseveen and Romijn, 2015).

While the improved connection could bring more development and prosperity to the hubs, this could detract from the crossed area that is not connected to the line. People might move closer to the city, leading to more people leaving the less developed crossed area. A hyperloop connection could therefore contribute to the urbanization of the small station areas, but also to large differences in connectivity between different areas (Van Maarseveen and Romijn, 2015). Overall, as the hyperloop improves connection in already urbanized areas, it is likely to increase the gap between developed and underdeveloped parts in society.

6.1.4 Traffic Congestion

If the hyperloop can compete with other modes of transportation, also in costs, people might opt for the faster mode of transportation that the hyperloop provides. other modes of transportation such as plane, train, car and bus will then likely see a decline in use (Ricci, 2021). The decreased use of car and bus transport could have as a consequence that traffic will suffer less congestion. Decrease in train and plane use could make room in travel schedules and may have as a positive effect that there will be less delays and overbooked vehicles. An addition of another fast mode of transportation, such as the hyperloop, could therefore cause pressure relief and increased comfort also in other modes of transports.

A second factor that can relieve traffic congestion on highways is the possibility of the hyperloop to be used as a mode of freight transport. As the hyperloop can provide faster delivery times than trucks, the cargo transporter of certain time sensitive goods might opt for this form of transport rather than transporting by road. This will remove a significant number of trucks from the roads, relieving congestion (Dabrowska et al., 2021).

Congestion effects that could arise for a hyperloop system are when pods are delayed or inoperative. This might lead to the cancellation of booked seats and potentially the delay or cancellation of other pods. The scarcity in transport apparent in the non-availability of the desired departure and arrival times can be monetized to measure its impact on society (van Essen et al., 2019). To determine the net effect the hyperloop connection could have on traffic congestion, it will be useful to compare the gain from decongestion in other modes of transportation to the effect of possible congestion in the hyperloop system in relation to the probability of delay or failure of pods.

6.2 Safety

The safety of the hyperloop system is introduced briefly in Section 2.3. Since no full scale hyperloop system has been built yet and no safety standards exists, it is hard to assess the safety of the hyperloop system. For hyperloop development, it is therefore essential that safety standards are set in the near future that at least meet the European safety requirements, since these rules could have implications on pod and tube design.

6.2.1 Accidents

Unfortunately, accidents are almost inevitable for any mode of transportation. Fatalities and injuries happen in every form of transportation, both passenger and freight. To evaluate the safety of transportation options, costs are linked to injuries and fatalities caused by accidents. These costs can be divided into different categories, like medical costs, production losses costs, human costs, administrative costs and material damages (van Essen et al., 2019). The type of injury (fatality, serious injury or slight injury) for the victims in an accident has an effect on these costs. For example, in the EU, the average human costs for a fatality is € 2,907,921 (van Essen et al., 2019). The total external accident costs for land-based modes of transportation in the EU are € 281,700,000,000 (van Essen et al., 2019). The prevention of accidents and, thus, the safety of the system is undoubtedly of utmost importance.

To make assumptions on the safety of the hyperloop, its operation characteristics can be compared with other modes of transportation. Hyperloop vehicles moves along a fixed track just like rail. Important differences between rail and the hyperloop however are enclosure and automated operation. Since hyperloop pods move in a closed off tube environment, no objects or people can intrude the path of a passing pod. Pods are fully automated, while trains and also cars are still being operated by humans. This means that there is still room for human error, which is the most common cause for road accidents (Perchonok, 1972; U.S. Department of Transportation, 2018). For rail, human errors, technical failure and external intrusions are the most common causes for accidents ("Railroad Accidents: Common Causes, Statistics and Prevention", n.d.; Kim and Yoon, 2013). The closed-off tube environment and automated operating system could therefore mean that the number of accidents is lower for the hyperloop than for rail. The hyperloop could also take over passengers and freight from cars and trucks, reducing the number of people and vehicles on the road and therefore reducing the amount of accidents on the road as well.

When an accident does occur, chances are high that this is due to technical malfunctions. Safety systems on the pod should make sure that the pod is able to safely stop and reach safe havens to let passengers out when any subsystem in the pod or track fails. In the unfortunate event where pods do make contact with other pods or the tube, or any other accident that could occur, the high cruising speed of the pod makes a crash very dangerous for passengers inside, increasing the chances of serious injuries or fatalities. The tube is prone to damages from the outside, potentially causing large cracks and thus leaks in the tube. This could cause large pressure waves inside the tube, potentially forcing the pod from the guideway. Delft Hyperloop has done extensive research into the different emergency situations that could occur in the hyperloop system (Delft Hyperloop IV, 2020). To determine the exact level of safety of the hyperloop, the probability of these scenarios and their severity need to be thoroughly investigated and tested.

6.2.2 Perceived Safety

For passengers, the perceived safety of the hyperloop is also of importance. Moving in a small pod down an enclosed tube with 1000 kilometers per hour does not make everyone feel comfortable. The system needs to be designed such that passengers feel safe while traveling with the hyperloop.

Perceived safety starts at the station. Hyperloop stations will include a security screening for passengers, much like those at airports. These systems make sure that no passenger brings any dangerous items on the pod. Knowing that it is very hard to bring dangerous items on a hyperloop pod already makes passengers feel safer when traveling with the hyperloop, next to making traveling with the hyperloop safer in itself.

To make sure that people feel comfortable inside the pod, interior design choices such as light patterns and screens showing the outside world go by, can be implemented. This could reduce motion sickness and therefore improve comfort levels inside the pod (Bloch, 2018).

The automated characteristics of the hyperloop system could make passengers feel less safe. People already have trouble trusting in the safety of automated vehicles on the road (Hutson, 2017). Even though automation reduces the risk of accidents, people tend to trust human instinct more. With pods being driverless, this could make passengers feel less safe in the pod. This also means that when an emergency situation does occur, passengers will have to communicate with system control units through wireless connections, instead of for example having a cabin crew, like in airplanes, that can assist passengers. An example emergency situation could be malfunctions inside the tube infrastructure preventing the pod from finishing the trip, which means that passengers should potentially leave the pod at a safe haven. The pod should then be able to warn passengers about the situation without causing any panic. A different emergency scenario could be an on-pod emergency, where a passenger might be injured or unwell, requiring the pod to stop at the nearest emergency exit. In this case, passengers need to be able to communicate with control unit employees to make sure that the pod will stop at the nearest exit and emergency services are sent to the location. Calling for help through long distance communication instead of face-to-face, might make people feel less safe when traveling with the hyperloop compared to modes of transportation that use personnel on-board.

It should again be stressed that no hyperloop safety standards yet exist, nor have there been any safety test with a full scaled hyperloop system. The statements in this sections are merely assumptions on what effects the hyperloop could have on the safety of travelers.

6.3 User Benefits

In determining the external effects a new mode of transportation might bring, it is important to consider the benefits a user will experience from using the type of transport. In this section, different types of these user benefits will be investigated for the hyperloop.

6.3.1 Reliability

Reliability is an important factor for a mode of transportation to be successful. Reliability is the ability of a system to live up to the expectations of the users. It is thus very dependent on delays and disruptions of the schedule, and is most important for commuters and business people that need to travel frequently and need to be at certain places at certain times. The more reliable a system can be, the more stable it is perceived. An unreliable system risks losing trust of its users or even replacement by a more reliable service.

In this section, the cases where the hyperloop system might be unreliable are analyzed. The effect of these cases and the solutions will be investigated.

Causes and solutions for unreliability

Good reliability starts with good management of the schedule and the demand. If the operations of the hyperloop are well managed and adapted to the demand during the day, this could already take away possible delay or unavailability of seats. Since the hyperloop is a fully automated system, it would be ideal to make it very flexible and adaptive to the real time demand in the booking system. The hyperloop's turn-up-book-and-go system means that people can walk into the station, book a travel ticket on their phone and walk to the platform with their departing pod only moments later. Ideal would be, that any moment of the day, it is always possible to book a seat on a hyperloop pod that departs within 15 minutes. To deal with a fluctuating demand throughout the day, first of all it is important that the booking system anticipates on this in terms of ticket pricing.

Apart from this yield management, the hyperloop system could find flexibility in being modular. With the high frequency of pods that a hyperloop tube can take, it is quite easy to employ extra pods when the demand is there. As long as there is enough room between departure times to not exceed the maximum frequency and as long as there are additional pods that are ready to go, capacity can quite easily be increased. However, to have multiple pods on standby, will be inefficient and probably costly in terms of space. There would need to be a storage facility in the neighborhood of the station to ensure the fast deployment of new pods. In the case that enough space was found inside a city that the hyperloop station could be built there, finding additional space for a storage facility close by can be hard and expensive.

A well managed travel schedule can be disrupted due to emergency situations in and around the infrastructure or due to maintenance. The big difference between the two is that the latter can be planned. If a maintenance job is well planned and communicated to the users, it will not make the system unreliable, since the expectations of the users were altered beforehand. Still, for the feeling of reliability, besides planning and communication, it is important that maintenance works are not too frequent and also announced very far ahead. This can be achieved in two ways that are both important and necessary. The first is, again, strong management of the system. Maintenance should be planned during low expected demand and should be efficient and effective to not have to return frequently. Also, a maintenance event should be communicated to users via clear and accessible means, for example through the booking system itself. Secondly, the hyperloop should have robust systems that do not require a lot of maintenance in the first place. This can be a costly investment, but one that will pay off. Since most of the hyperloop's technical parts are located in the closed off tube environment, maintenance can be elaborate and likely to temporarily shut down all operations. To be able to plan maintenance far ahead, the hyperloop system should have automated checks and monitoring of the systems that do not require humans entering the tubes. Sensors in the tubes and on pods should monitor the status of technical parts and be able to give estimations of when maintenance is due.

In the case of emergency situation, delay caused by this is always unexpected. The extent of the delay is dependent on the type of emergency situation, as discussed in Section 6.2, and the severity of it. For example, an in-pod emergency where a pod is able to reach an emergency exit safely, will only cause delay for the people inside the concerning pod. But, if a pod is stranded in a tube, the tube cannot be used until the pod is towed to the nearest safe haven or station, thereby delaying many more pods and people. For delays due to emergency situations it is important to have a resilient system. As soon as something goes wrong this needs to be instantly detected and an scenario ready to anticipate on the situation. This could be in the form of towing pods on stand by, automated pressure compartments in the tube, instant communication of delay to the stations and the possibility of the booking system to find alternative travel options or to give money back. The infrastructure itself should be robust and able to be back on track as soon as possible after an incident to continue operations. As with the safety standards, the responses to emergency scenarios for the hyperloop still need to be standardized, as no operative hyperloop exists yet. The solutions in this section are therefore assumptions and speculations.

Thus, a reliable hyperloop network features three key aspects. First of all, good management of the system is needed. This should come with practical schedules, planning, communication and overall smooth operations. Secondly, there need to be excellent systems that are in a good state of maintenance. Third and lastly, in case something does go wrong, it is important to have all the resources ready to get back on track again; the system must be resilient. As soon as one of these things starts lacking, the chances of disruptions and delay rise and the system becomes unreliable.

6.3.2 Time Savings

The travel time a user saves by choosing a certain type of transport over another is an effect that falls under user benefits. For the hyperloop, being an ultra fast mode of transportation, the travel time saving is also one of its main selling points. As the hyperloop will most likely be an additional means of transport between two cities that are already connected by other means, the time people save by using it will be important. However, in present day, to move from A to B in the shortest time is no longer the most important. As long as there is a possibility to conduct activities on board, the time spent inside a vehicle becomes less important (Molin et al., 2020). For example making phone calls in a car, or reading or writing reports inside a train, make it possible to use the time for traveling productively. Due to this, the Kennisinstituut voor Mobiliteit found that loss of time for traveling is valued less for road travel in recent years (Kennisinstituut voor Mobiliteitsbeleid, 2013). However the same study found that this time loss has actually gained value in recent years for travel by train. This is because it was already possible to read documents while traveling by train, before people could call from the car, and people travel longer distances by train than by car (Kennisinstituut voor Mobiliteitsbeleid, 2013). It seems that people still value shorter travel times, even though they can utilize their time during the trip. The hyperloop would thus contribute most to the user benefit by making it possible to work from the pod. This would be done by creating workstations in the chairs and making a fast internet connection from the pod to the outside world.

6.4 Environmental Effects

Constructing and using hyperloop infrastructure will have an effect on the environment and direct surroundings in the form of emissions and noise, like any other mode of transportation. This section evaluates those effects.

6.4.1 Emissions

The emission of gasses by the hyperloop system can be divided into three groups. The first are the gasses that are emitted when the system is operating. The second are well-to-tank emissions, which are emissions due to the production of energy used by the hyperloop system. The third are emissions due to the manufacturing and construction of the hyperloop infrastructure.

Emissions of Operation

The emission of harmful gasses during hyperloop operation can be divided into two groups, air pollutants and greenhouse gasses that induce climate change. With both types of emission, costs can be associated.

Air pollution costs are costs that are caused by toxic gasses (NH_3, NO_x, SO_x, dust particles) emitted by the transportation sector through the use of for example internal combustion engines (van Essen et al., 2019). These costs can be divided into four types: health effects, crop losses, material and building damage and biodiversity loss. The total external air pollution costs for land-based modes of transportation in the EU are €71,800,000,000 (van Essen et al., 2019).

The hyperloop system will (most probably) work on electricity, which means air pollution effects will be quite small. It cannot be assumed however that they are zero. Electric cars and trains still cause some air pollution through wear of brakes and tires. The hyperloop pod will levitate, so there will be no wear of components due to the movement of the pod. However, moving parts in the vacuum pumps needed to maintain a vacuum in the tube network could degrade because of wear, causing small dust particles to pollute the air. The costs will most likely still be very small, but they cannot be assumed to be zero.

Climate change costs are costs caused by greenhouse gasses (CO_2, N_2O and CH_4) emitted directly by the transportation sector by burning for example fossil fuels in internal combustion engines during operation. These emissions do not include the emitted gasses during the production of these fuels. These costs are related to the effects of climate change, such as sea level rise, biodiversity loss, water management issues, extreme weather and crop failures (van Essen et al., 2019). The total external climate change costs for land-based modes of transportation in the EU are €83,140,000,000 (van Essen et al., 2019).

As mentioned above, the hyperloop system will (most probably) work on electricity. Using electrical systems to power all hyperloop subsystems means that there will be no direct emissions of greenhouse gasses by the hyperloop infrastructure. Again, these costs do not include the negative effects caused by greenhouse gasses emitted through generating the electricity used by the system. Climate change costs can therefore be assumed to be very minimal. If some subsystems of the infrastructure were to be powered by hydrogen, water and oxygen would be emitted into the atmosphere, but these are not greenhouse gasses.

Well-to-Tank Emissions

Well-to-tank emissions are emissions due to the production of energy sources used in the transportation sector, such as petrol, kerosene and electricity. This includes all the emissions during the production of the energy source, from the extraction, processing to transport (van Essen et al., 2019).

It is very important to take these emissions into account when looking at the sustainability of the hyperloop concept. The hyperloop does not emit any harmful gasses during operation through the use of electricity, but if this electricity is produced by coal power plants, the environmental impact is still considerable. To ensure that the hyperloop is completely climate neutral, the electricity used in the system needs to come from sustainable energy sources, like wind or solar power plants. When this is ensured, the costs of well-to-tank emissions can be assumed to be 0.

Manufacturing and Construction Emissions

So far, the hyperloop does not emit a lot of harmful gasses during operation, nor are there a lot of well-to-tank emissions if the electricity that is used for the system is produced by sustainable sources. However, to really asses the emissions throughout the life cycle of the hyperloop, the emissions during the manufacturing and construction of the infrastructure have to be taken into account as well.

Since the hyperloop will be a completely new form of transportation, the entire infrastructure still has to be manufactured and built. This includes hundreds of kilometers of tube, hundreds of pods, substations along the track and end stations. Materials for this hardware have to be manufactured and machines that potentially run on fossil fuels need to be used to put everything together. This process will emit an enormous amount of harmful gasses and fossil fuels.

To give an example, Lee et al. estimated the greenhouse gas emissions during the construction of 185.4 kilometers of high-speed rail infrastructure in Korea (Lee et al., 2020). They estimated that the complete construction emitted 3.7 megatonnes of CO_2-equivalents, of which 92% was due to the manufacturing of materials used in the infrastructure. This is around 2% of the total amount of tonnes of CO_2-equivalent emitted by The Netherlands in 2020 (CBS, n.d.). The same length of hyperloop infrastructure will most likely emit even more, since HSR does not require the construction of a thick tube.

This shows that even though the operational emissions are very minimal, emissions due to the manufacturing and construction of the hyperloop are substantial. A life cycle assessment (LCA) of the hyperloop would provide good insights into the environmental effects of the hyperloop from cradle to grave.

6.4.2 Noise

Noise generated by traffic can cause serious health issues for people living in the surrounding areas, such as heart disease, stroke, dementia, hypertension and annoyance (van Essen et al., 2019). Placing new infrastructure can lead to more traffic but also more people living in the area, causing more noise disturbance with more people that are affected by it. The total noise disturbance change costs for land-based modes of transportation in the EU are €63,600,000,000 (van Essen et al., 2019).

There are two components of the hyperloop system that are expected to generate some noise disturbance during operation. The first are the vacuum pumps keeping the tubes at a near-vacuum level. However, these can be well insulated to keep noise levels at a minimum. It is therefore not yet clear how much noise they will generate. The second component that could generate some noise are the pods going through the tube. Since the tubes are not completely vacuum, there will still be a build up of air in front of the moving pods, especially at high speeds, causing vibrations in the tube. These vibrations will generate some noise, but it is unknown how much.

Even though there will be some noise generated by the hyperloop, most of the infrastructure will be built in sparsely populated areas where less people will be exposed to noise. A hyperloop tube would cause some disturbance only in cities. However, vacuum pumps only have to be placed every couple of kilometers (Delft Hyperloop III, 2019), so these can be strategically placed to not disturb any people living around the tube. In addition, the vibrations of the tube will be the largest when a pod is traveling at cruising speeds. These speeds will be obtained after accelerating from a city station, which means that the pod will have traveled a significant distance away from a city before reaching these speeds, causing less noise inside the densely populated areas surrounding the tube.

The construction of hyperloop infrastructure, however, will generate significant levels of noise, which could cause disturbances for the people living around the construction site. This can be kept to a minimum by, for example, restricting the times at which construction activities can occur (Murphy and King, 2014).

6.5 Spatial Effects

Having hundreds of kilometers of tube running through a country's landscape has numerous effects. This section highlights the impact the tube network will have on habitat, the aesthetics of the tube and the land use effects.

6.5.1 Impact on Habitat

Transport can have a very disruptive impact on natural habitats and the landscape around it due to its infrastructure. The handbook on the external costs of transport (van Essen et al., 2019) identifies three main negative effects on habitat by transport: habitat loss, habitat fragmentation and habitat degradation due to emissions. Next to these negative effects, the negative impact of the construction of the hyperloop is also assessed.

Habitat loss is caused by the amount of land that the infrastructure needed for transport takes up, taking away the natural habitats of animals and plants. This negatively affects the biodiversity of the surrounding area. Habitat fragmentation happens when infrastructure for transport, such as motorways, separates the habitat of wildlife, again negatively affecting the biodiversity of the surrounding area. Habitat degradation due to emissions is explained in Section 6.4.1.

The hyperloop network makes use of large tubes that run across the surface of the earth. There are three types of vertical alignments possible for these tubes: underground, on-ground and on support pillars above the ground. Delft Hyperloop V has done extensive research on the effect on biodiversity of these three vertical alignment options (Delft Hyperloop V, 2021b). Placing the tubes underground has the least effect on biodiversity, since there is no barrier that takes up space in nature nor is there any spatial fragmentation. However, even with the tubes placed underground, there will be subsystems such as vacuum pumps and safety exits placed above ground in order to be easily accessible for maintenance, so there will be some habitat loss. The on-ground option is the worst for habitat loss and fragmentation, since the tubes will form a physical barrier for plants and animals to cross. The support pillar option will also take away some habitat, but nature can still cross underneath the tubes, resulting in less fragmentation. For all three options, construction will result in both habitat loss, fragmentation and emissions.

The hyperloop infrastructure brings with it a considerable impact on habitat. However, this impact will be similar to that of a motorway or railway, resulting in similar habitat costs as these forms of infrastructure. The habitat costs in the EU in 2016 for road and high speed rail are €93,500 and €84,500 per kilometer respectively (van Essen et al., 2019). This is considerably less than the habitat costs for aviation, which are €437,500 per square kilometer. Even though aviation has no habitat fragmentation costs, the habitat loss due to the significant size of airports and runways is enormous, resulting in very high habitat costs.

The construction of hyperloop infrastructure will also have impact on the surrounding area. For example, the heavy machinery used during construction can severely damage the quality of the soil underneath the construction site (U. S. Department of Agriculture, 2000).

6.5.2 Aesthetics

Visual pollution is an important aspect of the social acceptance of infrastructure. Large structures can be considered intrusive and therefore unwanted in densely populated areas or nature. This is sometimes also called the 'Not In My Backyard' (NIMBY) principle. Having large structures like hyperloop tubes near people's houses could for example lead to a decrease in value of people's homes (Peter D. Kinder, n.d.). These people have to be compensated accordingly, potentially leading to extra costs associated with hyperloop construction.

Delft Hyperloop V has researched what the aesthetic effects of hyperloop infrastructure would be (Delft Hyperloop V, 2021b). This again depends on the vertical alignment of the hyperloop tubes. When placed underground, the tubes are out of sight, with the exception of some subsystems such as vacuum pumps and safety exits. This would be the most aesthetically pleasing option. The two above ground options would be more disruptive. Integrating the design of the tubes into the surrounding area could make the tubes less disruptive.

6.5.3 Land Use

When land is used for infrastructure, this land cannot be used for other, potentially profitable purposes. This (mis)use of land can be associated with opportunity costs. For example, in The Netherlands every square meter taken up by infrastructure costs €8,50 in opportunity costs outside of city limits (Arno et al., n.d.).

The opportunity costs associated with the hyperloop again depend on the vertical alignment of the tubes. When the tubes run underground, the land above the tubes can still be used for other purposes, eliminating opportunity costs. When the tubes are built on pillars, the space under the tubes can also still be used to a certain extent, also reducing opportunity costs. Hyperloop infrastructure can also be built close to existing infrastructure like rail and highways, where opportunity costs are already accounted for.

Chapter 7

Conclusions

To implement a hyperloop network in Europe, the largest barrier is not in the new technology. Most challenges will occur in the investments and the initial decision-making process. In this report, a complete overview of information is created for the stakeholders that are involved in this initial process.

The hyperloop is a new mode of transportation that is somewhere in between a train and a plane. It levitates and moves with the help of magnetic forces, moreover, it travels through low pressure tubes to reduce the air resistance. This way, the hyperloop can reach speeds of 1000 km/h. The hyperloop is completely electric. If the hyperloop is powered by green energy, this means that it could be a sustainable solution for the current transport industry. Passengers travel in the hyperloop in a so-called pod, that is comparable with a single train coach. The pod speeds through a tube that has a near-vacuum pressure level. The pod does not have any windows, because there would be nothing to see. The lack of windows in the pod is compensated by informative and moving screens. For the passengers it is also at all times possible to contact the control center of the hyperloop in case of a problem, as the pods themselves are autonomous. The hyperloop tubes are equipped with safe havens, where pods can dock and passengers can leave the system, in case of an emergency. As the hyperloop moves with large speeds of 1000 km/h, the system benefits from covering large distances at a time. The recommended length of a corridor is between 100 and 1500 km. Besides being fast, the hyperloop is also very efficient. By reducing rolling drag and air resistance, and using a linear motor, the hyperloop is ten times more efficient than an airplane.

The Organization of a Hyperloop Project

For the hyperloop system to be operational, a lot of tubes are needed. To place this large network of tubes, a diverse group of stakeholders is involved with varying degrees of power and interest. The hyperloop is a completely new form of transport and, therefore, there are no examples of hyperloop projects that have been executed that can be used as an example. Moreover, because of the size of the hyperloop infrastructure and project, there will likely be multiple parties involved in ownership and financing. For a positive outcome of the project, the structure and organization of the involved parties is very important. As the hyperloop is an international network, in Europe, it is important to point out that the realization of a network will be unlikely without the involvement of the European Union. For a new international network, from the EU standardization and certification is required. For the EU it is also beneficial to be involved with the development and implementation of the hyperloop network, for the following 3 reasons:

- The climate friendly character of the hyperloop can help the EU reach the European Green Deal,
- Implementing a new mode of international transportation can increase the mobility of European citizens,
- By being a frontrunner in the development of the hyperloop, the EU could improve its position on the world stage of technology, innovation and infrastructure.

In regards of the EU being involved in the development of a hyperloop network, this report has pointed out that there should come an overarching authority called the European Hyperloop Agency. This authority could have a role as initiator, by providing legislation and testing opportunities to involved parties. It could also play a role in the standardization, that is needed before implementation, and it could also play a role in the financing of the project.

Then on the national scale there are different collaboration structures for the realization of a hyperloop network. The project can be initiated by a public party, such as the government, or by a private party, such as a hyperloop company.

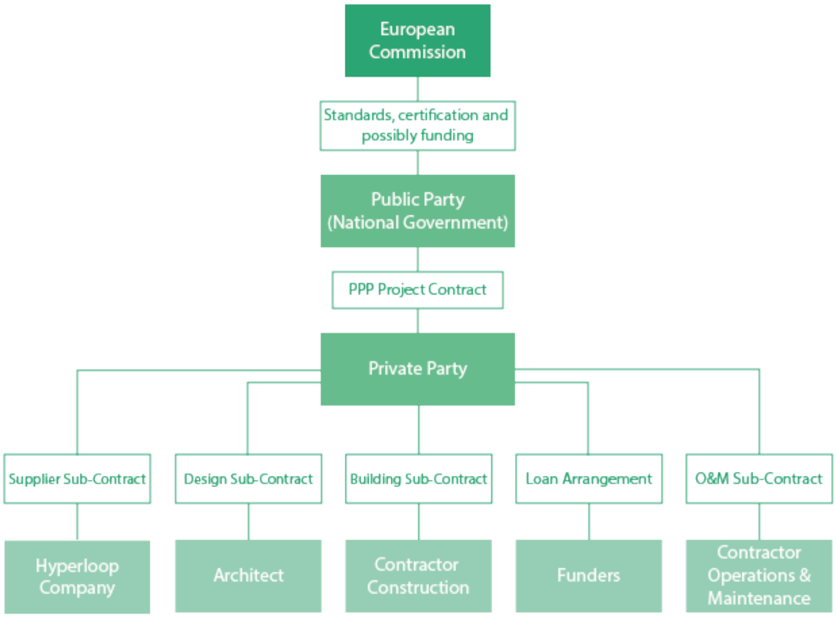

Figure 7.0.1: Participation strategy for a collaboration between private and public parties (Kishk, 2020).

Both structures have benefits and issues. The participation strategy for the hyperloop project that has been proposed as most effective and realistic in this report, is a collaboration between a public party and private parties. This structure is also shown in Figure 7.0.1. This collaboration can be in the form of legal and financial support from the government in a privately initiated project, or in the form of a PPP. In a PPP the private and public parties are co-organizers and often the government plays as a main coordinator. Even though the combination of private and public is the most probable collaboration strategy, this can still result in some issues such as complex structures and complicated coordination.

In a large project that is likely to be run by a combination of public and private parties, five phases can be distinguished. An overview of these phases is given in Figure 7.0.2.

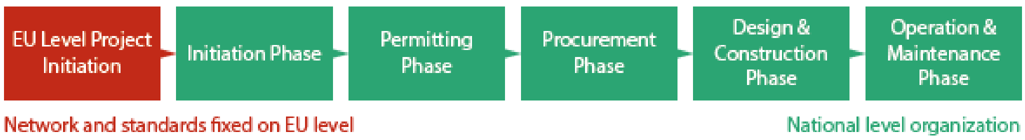

Figure 7.0.2: The five phases of developing a European hyperloop corridor.

The Decision-Making Around a Hyperloop Project

For initiators of the hyperloop infrastructure project, the decision-making process can be aided with a business case and an analysis of the external societal effects. As the hyperloop is still in a rather early stage, this report has only given a descriptive analysis of both.

Business Case

For the capital costs, it has been concluded in this report that, per kilometer, the hyperloop infrastructure will likely be in the same order of magnitude of existing forms of infrastructure such as rail- and highways. A large difference, however, is in the fact that for the hyperloop at least 100 km of infrastructure needs to be built at once for the hyperloop to be effective. Therefore, the starting capital costs of a single hyperloop corridor will reach multiple billions of euros.

As the hyperloop infrastructure is most likely to connect large cities, the demand will also be found here. The demand would come from business trips and commute for large companies in the cities, but demand could also come from the leisure sector. The hyperloop is expected to take over some travelers from competing modes of transportation, such as planes, trains and cars, that cover the same types of distances. In a market analysis for the hyperloop on the public transport market it has been found that the hyperloop will likely score well on timeliness, speed and comfort compared to other modes of transportation on the same distance region.

The main source of revenue for the hyperloop will be ticket sale, as holds for most modes of public transportation. However, inspired by airports, a share of income can also come from non-transport related sale at the stations. Nonetheless, the hyperloop's turn-up-book-and-go system invites people to spend less time at the station than they would at an airport. It may thus be expected that revenue from the hyperloop station will be lower than for airports.

Other sources of revenue can be found in multi-use of the infrastructure. The large network of tubes that is needed for the hyperloop system will connect multiple countries and could in some parts follow existing infrastructure to minimally disrupt the landscape. Additional revenue could be made from the tubes by:

- Using the tube network as energy storage,
- Integrating street lighting, signaling and advertisements along other infrastructure corridors,
- Combining the hyperloop tubes with other tube transport, such as water or hydrogen.

A visual representation of the findings of this report with regards to the business case, is given in Figure 7.0.3

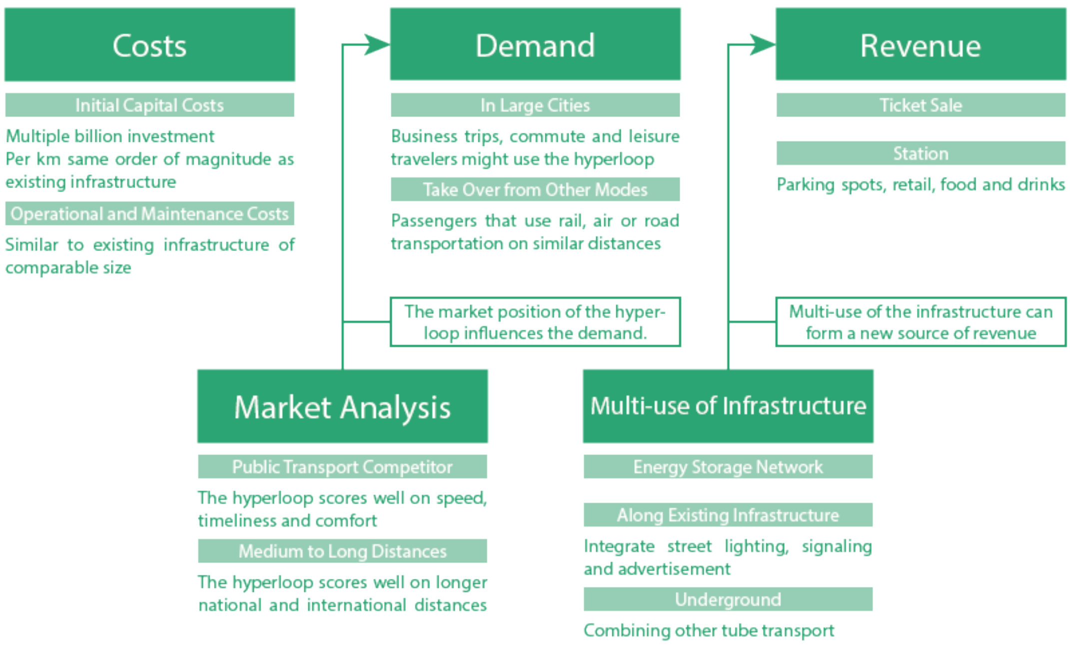

Figure 7.0.3: Visual summary of the business case of the hyperloop as has been found in this report.

External Effects and Social Merit

Next to an economic business case, societal external effects can help in the decision-making process, especially in the case of an infrastructure project with a large impact on society. In this report the possible external effects have been highlighted and explained.

The hyperloop can connect cities internationally with a very short travel time. The arrival of a hyperloop station in a city could have an effect on the employment, migration, housing and urbanization of that city, as people would want to live and work close to the station. This could benefit the economic growth of the city. However, as these effects are likely to be shift effect, people might be pulled away from other regions, and, as the hyperloop will probably come to an already large and prosperous city, these effect might increase the gap between developed and underdeveloped.

Since the hyperloop is an additional mode of transportation, it might have an alleviating effect on the traffic congestion problems in current modes of transportation.

As the hyperloop is a new mode of transportation, its safety needs to be extensively tested and proved, before the hyperloop can be commercial. The hyperloop is an autonomous vehicle, so in this report it is expected that accident due to human error will be much lower than in current modes of transportation. Because of the automation, however, perceived safety might be a more challenging aspect of social acceptance.

The hyperloop travels in tubes and therefore suffers very little external influences such as weather and interfering traffic. It would, therefore, benefit from adequate management to become a very reliable mode of transportation.

The fully electric hyperloop will not emit any greenhouse gases during operation. If the electricity is supplied by renewable sources, such as solar and wind energy, also its well-to-tank emissions are low. However, for the manufacturing and construction of the hyperloop infrastructure, it is expected in this report that emissions of harmful gasses and the use of fossil fuels might be unavoidable. Noise pollution from the hyperloop could be minimized by strategic placement of the vacuum pumps. The rest of the hyperloop system will be well insulated in the tubes.

Contrary to airplanes, the hyperloop uses large infrastructure over land. It will depend on the vertical alignment of the tubes per area how big the impact will be on habitats. For all tubes above ground, the aesthetics and visual pollution are aspects that might slow down the implementation of the hyperloop system. To limit land use it will be favorable for the hyperloop to follow existing infrastructure. In practice, however, this might be a hard task, as the hyperloop is not able to make sharp turns because of its high speeds.

A visual representation of the findings of this report with regards to the external effects and social merit, is given in Figure 7.0.4

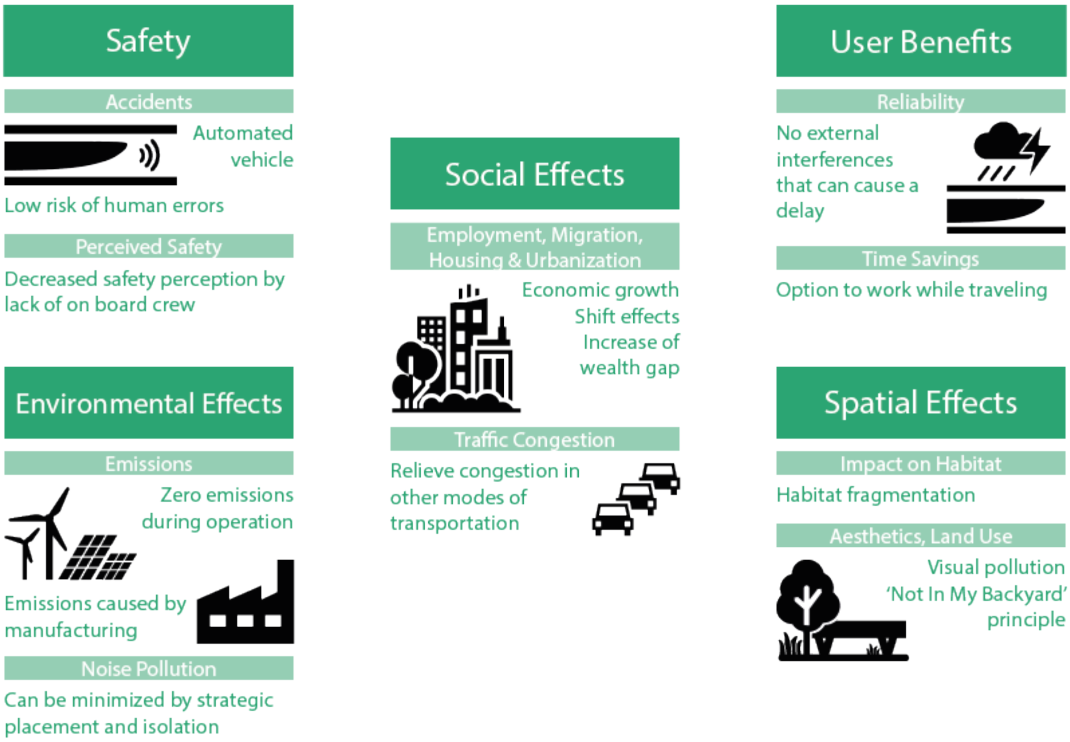

Figure 7.0.4: Visual summary of the external effects and social merit of the hyperloop that have been discussed in this report.

Barriers

The hyperloop seems to be a promising new mode of transportation for the future. Before its implementation though, there are still a lot of barriers to be overcome. First of all, there needs to come a standardization in hyperloop technology in order to implement it on a large, international scale. The most difficult part about this, however, is when to do this, as hyperloop technology is still a fast growing and fast changing sector.

Secondly, the international, large distance character of the hyperloop might create barriers between and within the participating countries. Between countries there needs to be good coordination in legislation and project management in order to successfully connect two parts of the network. Within one country, barriers can be found in spatial integration, economic differences and public interest.

The last barrier that the hyperloop faces has to do with the financing of the project. As already even a single hyperloop corridor is a large and risky investment, it may be difficult to find investors. It is therefore recommended that the hyperloop is tested and demonstrated extensively, in order to make it more attractive to investors.

Chapter 8

Recommendations

In this report the principles of the new mode of transportation that is the hyperloop have been collected and explained. The participation strategies and phases of the future implementation have been analyzed and different parts of a the hyperloop business case have been researched, as well as the barriers that the implementation of the hyperloop still faces. Also, the external effects and the social merit that the hyperloop could cause, have been investigated. This combined information could be a helpful starting point for bringing the hyperloop closer to implementation by creating clarity and awareness. It remains a fact that our modern world is in need of more sustainable ways of high speed transportation. To assess whether the hyperloop could be the solution, more research needs to be conducted. In this chapter, recommendations for further research are given.

Life Cycle Analysis

A life cycle analysis is often used to quantify the total environmental impact associated with a certain product or project, and could therefore be used to do this for the hyperloop. It assesses the total environmental impact, from manufacturing all material needed to construct the system to the point where parts of the system need to be replaced, resulting in waste in the form of the replaced parts. The hyperloop is promoted as an energy efficient system that could be completely powered by green energy, resulting in a very small carbon footprint during operation. However, the manufacturing of all the components needed for a tube network of thousands of kilometers in length will emit enormous amounts of green house gasses and harmful pollutants. An LCA could aid in calculating the amount of greenhouse gasses emitted by the hyperloop system during manufacturing and construction. The result can then be used to calculate how many years the hyperloop system should be operational to emit, in total, less green house gasses than, for example, aviation in the same period of time.

An LCA could also aid in researching the wear of components in the hyperloop infrastructure such as the tube, thus calculating how long a component can last before it needs to be replaced. This would contribute to more accurate estimations of the operational and maintenance costs.

Lastly, an LCA can also be used to help make a trade off between the two types of propulsion system that can be used by the hyperloop pods. Looking only at the advantages and disadvantages of both the LSM and LIM propulsion technologies in terms of costs, calculations can be done to work out how long an LSM propulsion should be operational for, to save enough costs on energy consumption to equal the extra capital costs over an LIM propulsion system.

Drivers for the hyperloop Implementation

To aid the hyperloop implementation, it needs to be very clear what the drivers are for different parties to implement the hyperloop. This goes further than only making profit through tickets or saying that the hyperloop is more sustainable than, for example, aviation. These drivers need to be concrete and worked out. For example, for a national government, it can be a driver to invest in the hyperloop development to attract the hyperloop companies and therefore smart people to them and to eventually create an export product that is connected to their country. Another driver could be that kerosene gets taxed, making flying no longer affordable for a large part of the population, making the hyperloop an even more compelling solution. A clear overview of these drivers can then be presented to interested parties, potentially getting them even more interested in implementing the hyperloop.

Standardization and Safety

It has been mentioned multiple times before, but developing technology and safety standards is of utmost importance if the hyperloop were to be a success. Standardization in both technology and safety can give a more clear picture of what a hyperloop system should look like, so that developers of the hyperloop can design their systems accordingly. A European governing body can aid the development of standards, mediating between the multiple parties and stakeholders that want to have a say in these standards.

Multi-use of Infrastructure

With the high costs that come with the implementation of the hyperloop, any source of extra revenue would make for a more compelling business case. These extra sources of revenue could potentially come from using the tube infrastructure for other purposes as well. Some examples have been given in Section 4.5, but there could be many more ways to use the tubes to create more income for the owner of the system. It is therefore recommended to research potential sources of revenue through the multi-use of infrastructure.

Demand

To aid feasibility studies, it would be beneficial to do more accurate demand projections for hyperloop. Ticket price estimations are highly dependent on demand, so more accurate demand projections can result into more precise ticket price estimations and therefore a better insight of the feasibility of a certain hyperloop corriodr.

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Appendix A

Characteristics of the Hyperloop

The concept of the hyperloop that is sketched by Delft Hyperloop is based on a number of assumptions. There are a lot of different assumptions on different aspects of the hyperloop, since there is no operational hyperloop system yet, and involved parties are still speculating and working on designs. In Table A.0.1 the assumptions on different aspects that were found in literature are given, together with the assumptions that Delft Hyperloop has made, based on this.

Table A.0.1: Overview of assumptions on the hyperloop found in literature.

Aspect	Value	Unit	Motivation	Value 1	Unit	Source	Value 2	Unit	Source	Value 3	Unit	Source	Value 4	Unit	Source
Weight of pod	20000	kg	Between Musk's first estimation and the average weight of a MagLev train, which has similar components.	15,000	kg	Musk, 2013	25,000 - 30,000	kg	Zhai et al., 2019						
Cruising speed	1000	km/h	Used in most papers on hyperloop, nice round, easy to remember number.	700	km/h	Dabrowska et al., 2021	1000 - 1200	km/h	AECOM, 2020	1200	km/h	Museros et al., 2021	1159	km/h	Taylor et al., 2016
Inner tube diameter	3.5	m	Large enough to fit a passenger hyperloop pod. Suitable for the carrying of both people and cargo.	3.5	m	Delft Hyperloop III, 2019	2.5	m	Dabrowska et al., 2021	3	m	AECOM, 2020; Arup et al., 2017			
Pillar spacing	30	m	Commonly used. Santangelo, 2018: "In the infrastructure industry the average span is usually between 20 m to 40 m." (Santangelo, 2018)	30	m	Musk, 2013	30	m	Delft Hyperloop III, 2019	20 - 40	m	Museros et al., 2021			
Seats per pod	48	-	Fits in 16 rows of 3, combines a reasonable capacity per pod, while the pod is not too long to take turns at low speeds.	50	-	Delft Hyperloop III, 2019	28	-	Musk, 2013						
Tube pressure	100	Pa	Supported by several papers. Cost of maintaining the vacuum increases steeply for pressures lower than 100 Pa (Decker et al., 2017).	3 - 50	Pa	Delft Hyperloop III, 2019	200	Pa	Decker et al., 2017	100	Pa	Opgenoord and Caplan, 2018; Musk, 2013; Sane, 2020	30 - 200	Pa	Delft Hyperloop IV, 2020
Pod frequency	120	s	Frequent enough to reach good capacity, possibility to increase frequency when demand increases.	30	s	Delft Hyperloop III, 2019	30 - 120	s	Musk, 2013						
Length of corridor	100 - 1500	km	At least long enough to reach top speed. After 1500 km the energy consumption per km per person for airplanes drops to a level that they can compete with a hyperloop in speed and energy consumption (Federici et al., 2009; Musk, 2013).	100 - 500	km	Dabrowska et al., 2021	300 - 1500	m	Delas et al., 2019						
Capacity of one tube	1500	pass./h	based on 50 passenger pods leaving every 2 minutes	840 - 3360	pass./h	Taylor et al., 2016	20,000	pass./h	Dabrowska et al., 2021						

Appendix B

Lengths and Sizes of Route parts

For an acceptable level of comfort, a maximum lateral acceleration of the pod of 0.4 G is assumed (AECOM, 2020). With this, the minimal radius of a turn can be calculated, using Equation B.0.1, given the cruising speed of the hyperloop.

$$a_{\text{max,lateral}} = \frac{v_{\text{cruise}}^2}{R_{\text{turn}}} \tag{B.0.1}$$

With $v_{\text{cruise}} = 1000$ km/h, this results in $R_{\text{turn}} = 19.7$ km.

With this radius, the length of a high speed switch may be calculated. That is, the length of the tube in the y-direction before a distance of at least the width of the tube has been passed in the x-direction, while obeying the minimal radius of the turn. A sketch of the switch is shown in Figure B.0.1.

The minimal length of the switch, $l_{\text{min,switch}}$, can be calculated using the geometric formula in Equation B.0.2.

$$l_{\text{min,switch}} = \sin\left(\arccos\left(\frac{R_{\text{turn}} - w_{\text{tube}}}{R_{\text{turn}}}\right)\right) \times R_{\text{turn}}, \tag{B.0.2}$$

where w_{tube} is the width of the tube, which is estimated to be 4 m, to account for the thickness of the tube wall. This results in a minimal length of the switch of $l_{\text{min,switch}} = 397$ m. To simplify the result, this is rounded up to the following assumption of the length of a switch: $l_{\text{switch}} = 400$ m.

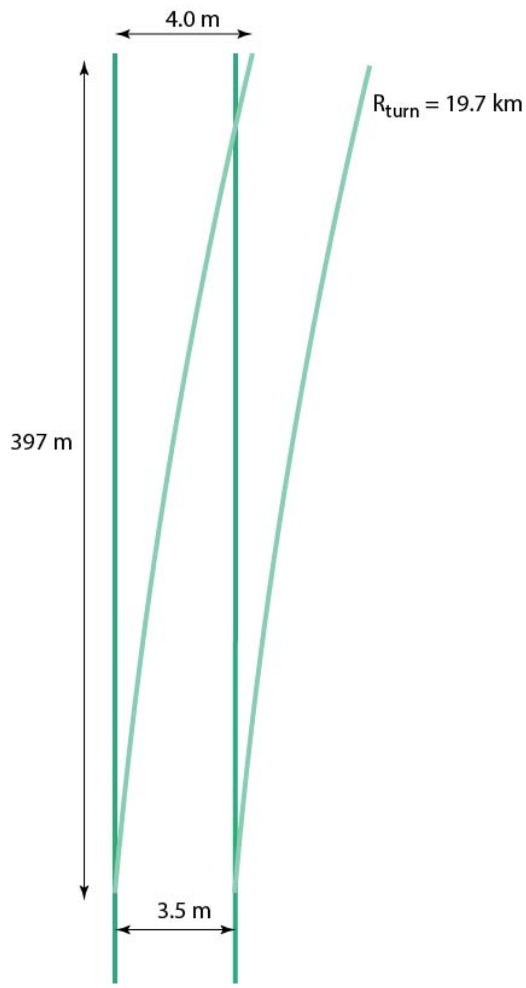

Figure B.0.1: Schematic drawing of a high speed switch with corresponding sizes. Figure is not to scale.

Appendix C

Business Case - A Hyperloop Corridor between Amsterdam and Paris

In this chapter, an example business case of a hyperloop corridor between Amsterdam and Paris is worked out. The goal of the business case is to concretely demonstrate how certain aspects have an effect on ticket prices for the hyperloop and thus how to work out a corridor business case. In this example, hyperloop ticket prices are calculated for multiple demand scenarios. A number of assumptions have to be made on the costs of hyperloop infrastructure and operation, as well as the demand and return on investment (ROI). With these variables, several demand scenarios are worked out, resulting in a ticket price for each scenario. These ticket prices will be compared with ticket prices for the high speed train connection between Amsterdam and Paris, the Thalys, plane tickets and traveling by car.

It should be noted that these assumptions are made with the information we have today (June 2022). With hyperloop technology developing fast, concrete numbers can be concluded from tests and potentially even first hyperloop corridors. These assumptions can therefore differ from future numbers, when more tests have been done and/or the hyperloop is actually implemented.

The demand numbers used in this business case are merely to demonstrate the ticket prices at these demand levels. They are therefore not accurate projections, but serve as an indication of potential, future ticket prices.

C.1 Assumptions

C.1.1 Corridor Specifics and Operations

The hyperloop tube between Amsterdam and Paris will be a double way tube of 500 kilometers in length. Operational times will be between 6:00 and 22:00. The maximum demand that the corridor can handle is 1 pod leaving per 30 seconds. The corridor will include all three vertical alignments (on pillar, on ground and under ground).

C.1.2 Costs

Capital Costs

As stated in Section 2.6, there have been multiple estimations on the costs of hyperloop infrastructure per kilometer. The costliest estimation was done by Delft Hyperloop, estimating the costs of a double-way tube running underground at a maximum of 45 million EUR€/kilometer (Delft Hyperloop V, 2021b). However, Delft Hyperloop's calculations do only include the costs of the tube and construction, emergency shafts, protection costs and land acquisition. To account for all the other elements in the list of aspects included in capital costs given in Section 4.1.2, estimations by AECOM are used, which estimate the accounted aspects by Delft Hyperloop to be around 70% of all capital costs (AECOM, 2020). The average capital costs in this business case are therefore estimated to be 60 million EUR€/kilometer. The total capital costs thus are **30 billion EUR€**.

Operational and Maintenance Costs

To estimate the total operational and maintenance costs, first the operational and maintenance costs of the English railway system are used. In 2017, this was 1.2 million EUR€/kilometer (Smart Transport, 2021). For the hyperloop corridor between Amsterdam and Paris, this results in 600 million EUR€ of operational and maintenance costs. Since the railway system does not include security systems, which contribute a considerable amount to the operational costs of Schiphol each year, and maintenance costs will most likely be higher due to the many components in hyperloop infrastructure, the operational and maintenance costs are estimated to be **1 billion EUR€/year**.

C.1.3 Return on Investment

The return on investment time is estimated to be **25 years**.

C.1.4 Demand

Demand will be used as the changing variable to calculate ticket prices. By using different demand estimations, three scenarios will be evaluated. For simplicity, daily demand is assumed to be the same throughout a full year. This is of course not in line with real life travel demand, since travel demand grows during periods like public holidays. To form the scenarios, the daily demand for travel between Amsterdam and Paris using the Thalys and planes from 2019 (pre-COVID19) is used.

In 2019, 7.85 million people used the Thalys, of which 21% used the train to travel between Amsterdam and Paris, resulting in an average of around 4500 passengers per day (Wikipedia, 2022). In the same year, around 2,600,000 people flew between Paris CDG + Paris ORLY and Amsterdam Schiphol, resulting in an average of around 7100 passengers per day (Eurostat, 2022a, Eurostat, 2022b). There is no data on the number of people that travel between Amsterdam and Paris by car everyday. To take these people traveling by car into account, **the total number of daily passengers between Amsterdam and Paris is estimated to be 12,000 on average**.

C.1.5 Ticket Prices

The goal of the business case is to use the fixed values for the costs and ROI and the different demand scenarios to calculate ticket prices. These prices will be compared with other transportation options that currently exist between Amsterdam and Paris, such as the Thalys, airplanes and the car.

C.1.6 Others

Other considerations or assumptions made in this business case are:

- Sources of revenue created by the station discussed in Chapter 4.3 are not included.
- Sources of revenue through multi-use of hyperloop infrastructure such as the use of solar panels on top of the tube are not included.
- The hyperloop corridor between Amsterdam and Paris could also be used by pods that have Brussels or Southern European countries (if origin station is Amsterdam) as their destination. The tickets for these connections will also help fund the discussed corridor, but they are not taken into consideration here.
- The whole system (tube, stations, pods) has one single owner entity.

These considerations and assumptions will most likely result in higher ticket prices, which means that the results of this business case are for a worst case scenario where the hyperloop only generates revenue through selling tickets.

C.2 Current Transportation Options

The most used transportation options to travel between Amsterdam and Paris today are by train, plane and car. These modes are compared in terms of travel time and expenses for a one-way trip in Table C.2.1.

Table C.2.1: Current Options of Transportation between Amsterdam and Paris.

Name	Thalys	Direct Flight	Car (gas)
Travel time*	3 hours and 20 minutes	1 hour and 20 minutes	5 hours
Expenses**	€100 - €215	€120 - €400	€80

*Flight time does not include time at airports, which could add 2.5 hours in total.
**Prices are as of June 2022. Prices range due to time of day, days in advance of booking and chosen airline. Average gas prices in the Netherlands and average mileage of gas powered car are used (€2.283 at 1 L per 14 km).

C.3 Ticket Price Calculation

The following equation is used to calculate the ticket price of a seat on a hyperloop pod between Amsterdam and Paris.

$$p_{ticket} = \frac{c_{cap} + (c_{O\&M} * ROI)}{ROI * 365 * d} \tag{C.3.1}$$

Here p_{ticket} is ticket price in euros, c_{cap} are the capital costs in euros, $c_{O\&M}$ are the yearly operational and maintenance costs, ROI is the return on investment time and d is the demand in passengers per day.

C.4 Scenarios

Ticket prices will be assessed for a number of different demand scenarios. In the 25 years ROI time, the demand is expected to grow in each scenario throughout the years. This is why in each scenario, the 25 years are broken up into 3 sections. The first two years after implementation make up the first section. During this time, mainly early adopters will use the system. This time will serve as a proof of concept, showing potential hyperloop users what benefits the system offers. The next 10 years will serve as the second section. During this time, more and more existing passengers between Paris and Amsterdam will make use of the hyperloop, also taking into account new passengers traveling between Paris and Amsterdam due to the benefits of the hyperloop system. The last 13 years will serve as the third section. In this section, the global growth in travel demand will be accounted for. In each section, it is assumed that ticket prices will stay the same.

C.4.1 Poor Demand

In this scenario, the demand for the hyperloop corridor is assumed to be on the low side. In the first two years, only 50% of existing daily passengers between Amsterdam and Paris in 2019 will make use of the system. In the 10 years after that, 83% of existing daily travelers will use the hyperloop. In the 13 years after that, the hyperloop will have taken over all currently existing passengers between Amsterdam and Paris. Ticket prices are adjusted accordingly. The results are show in the table below.

Table C.4.1: Hyperloop ticket prices in the first 25 years - poor demand scenario.

Time (years)	Number of daily passengers (-)	Ticket price (EUR€)
2	6000	642
10	10000	600
13	12000	532

The results show that it is not likely that people will travel with the hyperloop, since even in the last 13 years, tickets cost more than double those of the Thalys.

C.4.2 Expected Demand

In this scenario, the demand for the hyperloop will roughly be along the assumptions made on the growth in demand. The first two years will have 83% of existing travelers traveling with hyperloop. In the next 10 years, the hyperloop will have taken over 100% of existing travelers in 2019 plus additional passengers generated by the hyperloop. In the 13 years after that, the number of daily passengers has accounted for a growth in demand for travel. Ticket prices are adjusted accordingly. The results are shown in the table below.

The results show that the ticket prices for the first year remain very high, decreasing slightly when compared to the poor demand scenario. However, ticket prices in the last 13 years now can compete with those for last minute plane tickets.

Table C.4.2: Hyperloop ticket prices in the first 25 years - expected demand scenario.

Time (years)	Number of daily passengers (-)	Ticket price (EUR€)
2	10000	598
10	14000	426
13	18000	338

C.4.3 High Demand

In this scenario, the demand for the hyperloop is assumed to be high. The first two years, hyperloop will take over all existing passengers between Paris and Amsterdam. In the 10 years after that, demand for the hyperloop will grow enormously, already taking into account the growth in demand for travel, which will accelerate due to the implementation of the hyperloop. The last 13 years, this trend will continue. Ticket prices are adjusted accordingly. The results are shown in the table below.

Table C.4.3: Hyperloop ticket prices in the first 25 years - high demand scenario.

Time (years)	Number of daily passengers (-)	Ticket price (EUR€)
2	12000	445
10	20000	310
13	30000	200

The results show that the price for early adopters in the first 2 years has dropped substantially. The ticket prices in the next 23 years now also have a better competitive position with respect to the ticket prices of the Thalys and airplanes compared to the previous scenario. However, even in the highest demand section, tickets will not be lower than 200 EUR€ without making tickets prices in the first 12 years substantially more expensive. ()

C.5 Conclusion

The results of this business case on a hyperloop corridor between Amsterdam and Paris show that the demand for the system needs to be substantial in order for ticket prices to be competitive with those of existing modes of transportation between these cities. However, it should again be noted that all assumptions are on the conservative side.

First, the capital and operational and maintenance costs are estimated higher than estimations done in previous research. This is done to account for contingencies that often lead to inaccurate cost projections in infrastructure projects. However, there is also the possibility that these cost estimations are accurate, potentially resulting in lower ticket prices.

Second, as stated in Subsection C.1.6, it is assumed here that the only revenue generated by the system is through selling tickets. However, there are other sources of revenue that can contribute to lower ticket prices, such as the hyperloop station (Section 4.3) and multi-use of infrastructure (Section 4.5). It is now also assumed that this corridor is paid back through the tickets for seats on pods traveling between Amsterdam and Paris, but the same tube will also be used by pods traveling to Brussels and pods that travel from Amsterdam to the south of Europe. These tickets will also be used to pay back the investments for this corridor.

Lastly, ticket prices in the first two years are for all scenarios very high compared to competitors of the hyperloop. To account for this, national governments or the European Union could subsidize hyperloop tickets in order to make the hyperloop more competitive in the first years after implementation, encouraging passengers to use the hyperloop to help grow demand and not use more environmentally damaging modes of transportation.