# Bachelor-Thesis an der Hochschule Luzern - Technik & Architektur

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| **Titel** | **Modeling the operating costs of an Hyperloop connection from Zurich to Paris** |
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**Abstract Deutsch**

Die steigende Nachfrage nach Verkehrsdienstleistungen erfordert eine Revolution im Sektor, um Wachstum zu ermöglichen und gleichzeitig den Umwelteinfluss zu minimieren. Die Hyperloop-Technologie bietet eine neuartige Lösung: Röhren mit nahezu Vakuum ermöglichen einen Hochgeschwindigkeitstransport mit geringem Energiebedarf. Trotz seines Potenzials ist die finanzielle Machbarkeit des Hyperloops, insbesondere in Bezug auf Betriebskosten, noch wenig erforscht. Diese Studie bemüht sich, die Kosten einer hypothetischen Hyperloop-Verbindung von Zürich nach Paris zu modellieren, um das Verständnis dieser Kosten zu vertiefen und Ansätze für zukünftige Forschungen zu identifizieren.

Die Untersuchung umfasst die Definition des Szenarios von Zürich nach Paris, basierend auf aktuelle Informationen, die durch Desk Research gesammelt wurden. Dies geht der Entwicklung eines Kostenmodells für den Hyperloop voraus, das auf den im Eisenbahnsektor vorherrschenden Kostenmodellen basiert. Anschließend wird das Modell mit relevanten Parametern versehen, um Simulationen zu ermöglichen, darunter eine Basissimulation für die wirtschaftlichste Variante, eine Sensitivitätsanalyse zur Ermittlung einflussreicher Parameter und eine Monte-Carlo-Simulation zur Bestimmung der Sicherheit von Kostenprognosen.

Die Basiskapitalkosten betragen 38 Milliarden Dollar oder 70 Millionen Dollar pro Kilometer. Der bedeutendste Einfluss auf die Kosten, etwa 70%, ergibt sich aus der Streckeninfrastruktur, während Stations- und Kapselkosten jeweils einen unwesentlichen Anteil von 1% darstellen. Die Monte-Carlo-Simulation ergibt einen Medianwert von etwa 1,5-mal der Basislinie, bei 62 Milliarden Dollar, mit einer Wahrscheinlichkeit von 95%, dass die Kosten zwischen 48 und 78 Milliarden Dollar liegen.

Die jährlichen Betriebskosten werden auf 530 Millionen Dollar geschätzt, hauptsächlich aufgrund des Energieverbrauchs. Die Sensitivitätsanalyse zeigt, dass diese Kosten stark von der Anzahl der Passagiere und der zurückgelegten Kilometer abhängen. Die Monte-Carlo-Simulation für Betriebskosten ergibt einen medianen Jahreskostenwert von 1,13 Milliarden Dollar, fast das Doppelte der Basiskosten, mit einer Wahrscheinlichkeit von 95%, dass die Kosten zwischen 800 Millionen und 1,47 Milliarden Dollar liegen werden.

Dieses Projekt betont die inhärente Unsicherheit bei der Schätzung der Hyperloop-Kosten aufgrund unbekannter Systemeigenschaften. Die Validität des Kostenmodells hängt von einer gründlicheren Forschung in die Technologie und der Entwicklung einer genauen technischen Konfiguration ab. Die Ergebnisse unterstreichen die Bedeutung einer effizienten Streckenplanung, insbesondere zur Minimierung der kapitalbezogenen Streckenkosten. Dies erfordert weitere Forschungen zu kosteneffektiven Tunnelbau- und Streckenoptimierungsmaßnahmen. Die Betriebskosten hängen hauptsächlich von den zurückgelegten Kilometern und der Passagierzahl ab, was auf die Notwendigkeit einer genaueren Nachfrageprognose für verbesserte Kostenprognosen und Infrastrukturplanungen hinweist.


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**Abstract**

The escalating demand for transport services necessitates a revolution in the sector to accommodate growth while minimizing environmental impact. The Hyperloop technology presents a novel solution, featuring near-vacuum tubes facilitating high-speed transport with low energy requirements. Despite its potential, the financial feasibility of the Hyperloop, particularly concerning operating costs, remains under-explored. This study endeavors to model the costs of a hypothetical Hyperloop connection from Zurich to Paris, aiming to advance the understanding of these costs and identify avenues for future research.

This investigation involves defining the scenario from Zurich to Paris, informed by contemporary information gathered via desk research. This precedes the development of a cost model for the Hyperloop, which is constructed based on cost models prevalent in the rail industry. Subsequently, the model is populated with pertinent parameters to facilitate simulations, including a baseline simulation for the most economical variant, a sensitivity analysis for determining influential parameters, and a Monte Carlo simulation to ascertain the certainty of cost predictions.

The baseline capital cost is \$38 billion, or \$70 million per kilometer. The most significant impact on costs, approximately 70%, stems from the track infrastructure, while station and capsule costs represent an inconsequential 1% each. The Monte Carlo simulation yields a median value around 1.5 times the baseline, at \$62 billion, with a 95% probability of the cost being between \$48 and \$78 billion. Yearly operating costs are projected at \$530 million, primarily resulting from energy consumption. Sensitivity analysis indicates that these costs are highly dependent on the number of passengers and kilometers traveled. The Monte Carlo simulation for operating costs presents a median annual cost of \$1.13 billion, almost double the baseline, with a 95% probability that costs will range between \$800 million and \$1.47 billion.

This project underscores the inherent uncertainty surrounding Hyperloop cost estimation due to unknown system characteristics. The cost model validity is contingent on more exhaustive research into the technology and development of a precise technological configuration. The findings highlight the significance of efficient route planning, especially in minimizing track-related capital costs. This invites further research on cost-effective tunnel construction and route optimization. Operating costs primarily depend on kilometers traveled and passenger volume, urging the need for more precise demand forecasting for improved cost predictions and infrastructural planning.

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## List of abbreviations and acronyms

Abbreviations and acronyms can be used freely once the full form or proper name has been established.

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| HSLU | Hochschule Luzern |
| Lucerne UASA | Lucerne University of Applied Sciences and Arts |
| ROW | Right of Way |
| TCO | Total cost of ownership |

# 1 Introduction

Nowadays, logistics is more present than ever. The consumer goods market is at an all-time high, with over 200 million parcels processed by Swiss Post alone in 2021 (Die Post, 2022). In the course of globalization, consumer goods and industrial goods travel through dozens of countries until they are finally used in their end destination. But logistics does not only concern goods but also the transport of people. According to the Swiss Federal Statistical Office, around 1 million Swiss people commute to work by public transportation every day (Bundesamt für Statistik, n.d.). The European turnover in the logistics sector was 1,150 billion euros in 2021 (Keller, 2022).

## 1.1 Starting situation

Logistics is an indispensable element in modern infrastructure. Transportation represents an essential core process of logistics. People and materials have to be moved from A to B for all value chains (Ihde, 2001). Transport routes have constantly been optimized and trimmed for efficiency, but there are not only positive aspects to modern transport routes. There is widespread agreement that modern transportation trends are unsustainable and that a fundamental change in the technology, planning, operation and financing of transportation systems is needed (Greene & Wegener, 1997).

A fundamentally revolutionary technology in the field of transportation, not only in terms of sustainability but also in terms of efficiency, is the Hyperloop approach. Such a system consists of a tube, which can be above or below ground, and corresponding capsules, which are transported through the tube. The advantage over conventional means of transport is that there is a partial vacuum in the tube to keep friction low and generate high speeds. Thanks to a generated magnetic field, the capsules are pulled through the tube and are accelerated while the capsules themselves float on a cushion of air. Therefore speeds of up to 1,200 kilometers per hour can be generated (Ross, 2016). This method of travel is not only faster and more environmentally friendly but also safer, more comfortable, immune to weather and environmental influences and also less expensive (Musk, 2013).

## 1.2 Research problem and objective

Especially related to the last-mentioned aspect, the question is how far an Hyperloop connection proves to be cheaper than a connection with conventional means of transportation. Due to the fact that Hyperloop is a concept and only test routes have been realized, the search for a reference project is unnecessary. For a better understanding of the basic concept, a fundamental understanding of the underlying cost structure is essential.

The aim of this project is to model the operating costs of an Hyperloop connection from Zurich to Paris. To achieve this goal, the following sub-goals are required:

- Development of a concrete scenario
- Elaboration of a cost model
- Parameterization of the cost model in the scenario
- Simulation of the model

Finally, the results found are analyzed and interpreted.

## 1.3 Structure of the thesis

An overview of the methodology used to approach the goals defined above can be seen in Figure 1. The underlying scenario of the work is realized with the help of desk research and literature review and results in the form of a use case. The primary goal is to define what the Hyperloop system will look like along the route in concrete terms. The cost model is obtained on a high level by qualitative desktop research. To tie the cost model to the Hyperloop concept at a lower level, qualitative literature review will also be used. The scenario and cost model are parameterized together. This will produce a model that reflects the operating costs of the Hyperloop connection for the defined scenario. This model will be implemented, parameterized, validated and verified. Subsequently, the model is simulated and tested by means of a sensitivity analysis, as well as a Monte Carlo simulation. The first enables the identification of variables with significant impact on costs, while the latter allows for the quantification of the expected costs as well as the error bounds of this estimation.

While the final chapter is devoted to analysis and interpretation, where three questions will be answered: (1) what are the expected operating costs of such a connection (result of the baseline simulation)? (2) to what certainty can the costs be predicted with the information available (result of the Monte Carlo simulation)? (3) And what are the parameters with the most influence on the operational costs (result of the sensitivity analysis)?

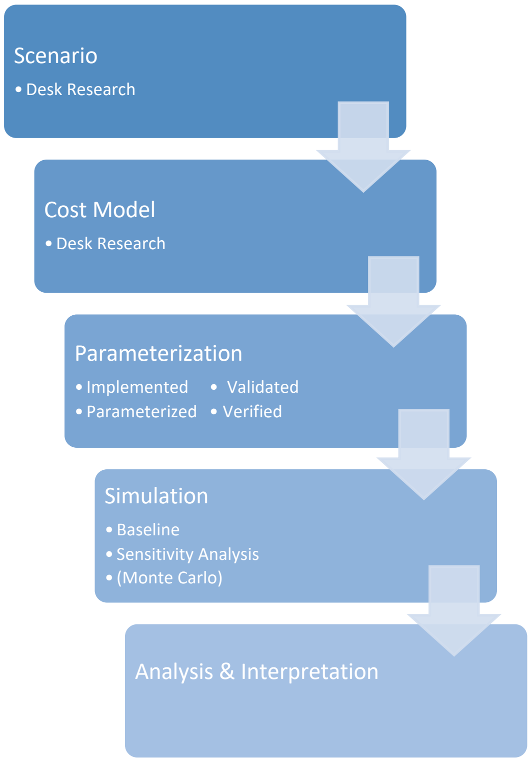


Figure 1 Overview Methodology

# 2 Foundations

This chapter covers an extensive literature research, which mainly deals with deriving the history of the Hyperloop technology as well as explaining the underlying technology in order to ensure a balanced foundation for the continuation of the thesis. Thereby, the historical development, from the first beginnings to later concepts and the current hype around the technology, is discussed. Furthermore, a brief overview of the basic technology behind the current Hyperloop systems will be developed to create a consensus of the technologies mentioned in later chapters. Moreover, the approach and the basic knowledge of the total cost of ownership (TCO) will be introduced to understand better how companies estimate the costs of capital goods. The exploration of this topic allows later in this report to model the total cost of ownership of a hypothetical Hyperloop connection and thus, not only the capital costs but all aspects of the later use of the connection.

## 2.1 History of the Hyperloop concept

In 1827, shortly before his death, George Medhurst published his ideas on compressed air propulsion under the title: "A New System of Inland Conveyance, for Goods and Passengers" (Medhurst, 1827). In it, he described how this compressed air could be used as a source of propulsion for the transportation of people and goods. He proposed to press air into a chamber and thus move a piston to set the transport unit in motion. Medhurst also proposes implementing his idea in a metal or stone tube equipped with a series of air compressors and pumps. His thoughts were never realized, but his writings influenced later developments, especially in the use of compressed air in the shipping and mining industries.

The idea of floating capsules and airless tubes did not end there. Quite the opposite, soon after, pneumatic tube systems were installed in numerous cities. These operate on the same underlying principle, the capsules in the tubes are either pushed away by compressed air or pulled in by suction. The arrangement is accomplished using air compressors, which are installed along the way, depending on the size of the system (Weinmeyer, 2021).
The London Pneumatic Despatch Company even tried to realize such a system on a large scale. Accordingly, the whole of London was to be tunneled with iron pipes for capsules large enough to transport parcels and even people at up to 50 km/h. However, the project was limited to only a few test sections and was abandoned after about ten years due to a lack of support (Förtsch, 2019).

Subsequently, there were repeatedly concepts and ideas of pneumatic railroads, driven by compressed air or suction in a mostly airtight tube. However, the majority remained ideas or short test tracks, such as the 95-meter-long pneumatic railroad operated by Alfred Ely Beach, shown in Figure 2. Ely Beach fought unsuccessfully with the authorities for permission to extend the line, so it eventually stayed at 95 meters and became a tourist attraction instead of a valuable means of transportation. Another problem of this construction was the inertia of the railroad (Beach, 1868).

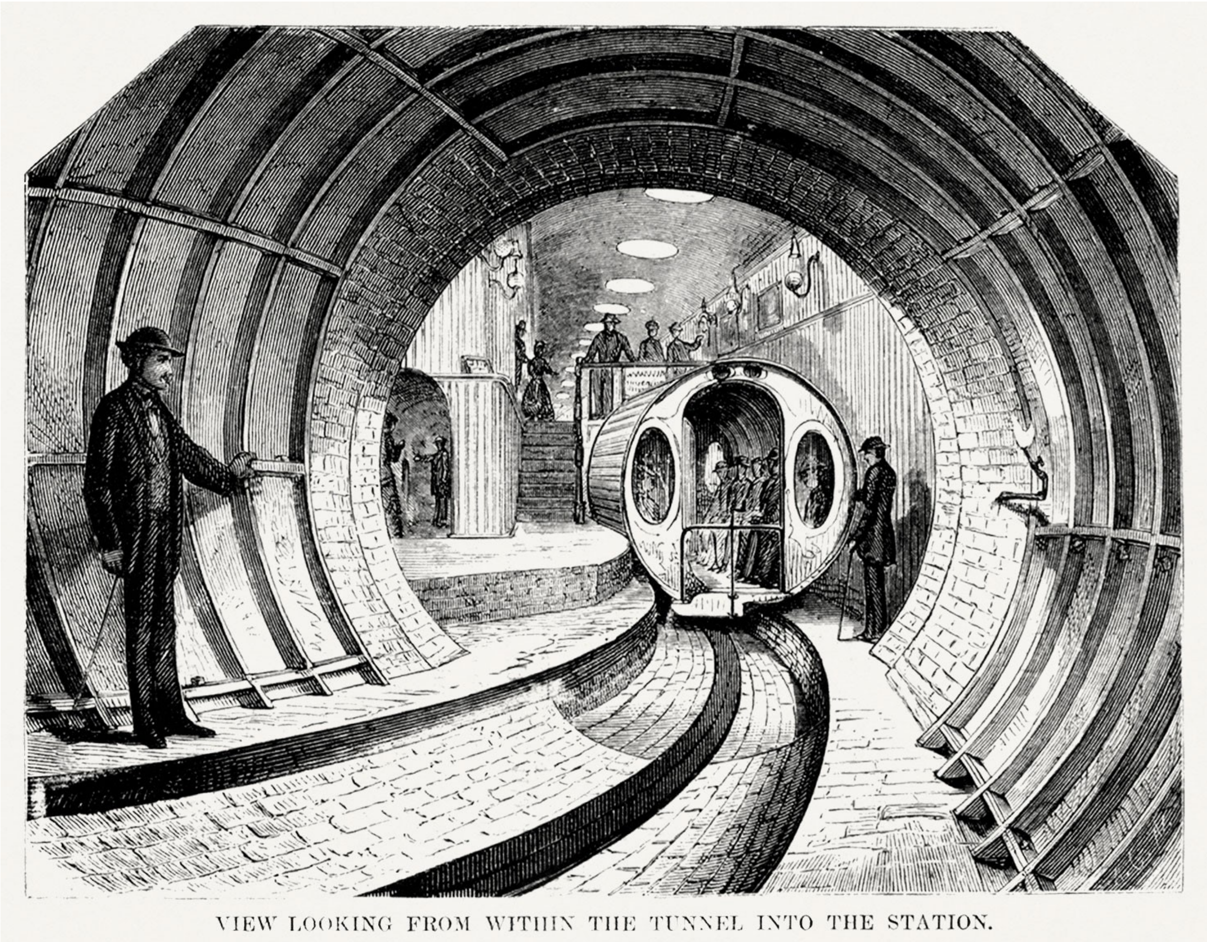


Figure 2 The Broadway Pneumatic Underground Railway from Alfred Ely Beach (Maier, 2022)

In 1904, a physics student and rocket engineer Robert Goddard developed a concept for a high-speed railroad that could cover the more than 300-kilometer distance from Boston to New York City in just 12 minutes. His vac-train, short for Vacuum Tube Transportation System, was based on a tube completely deflated by pumps to propel the capsule. The fundamental difference in his project, however, is that he does not use rails or wheels at all but instead uses strong electromagnets. These serve not only for acceleration and braking but also to counteract the problem mentioned above of inertia. In any case, Goddard estimates that the system can reach speeds of up to 1600 km/h (Streissguth, 1995). Five years after his death, in 1950, his wife was granted the U.S. patent for the vac-train (Figure 3).

Around the same time, the Russian Boris Weinberg developed a similar concept and, unlike Goddard, implemented it as a model, thus confirming the feasibility of the idea. However, one of the questions was how a capsule could be steered around a curve at such high speeds (Zaitsev et al., 2018).
Although the ideas were never really realized, they remain constant. Towards the middle of the 20th century, new concepts of tube trains were constantly emerging. And they all had one thing in common: It remained an idea.

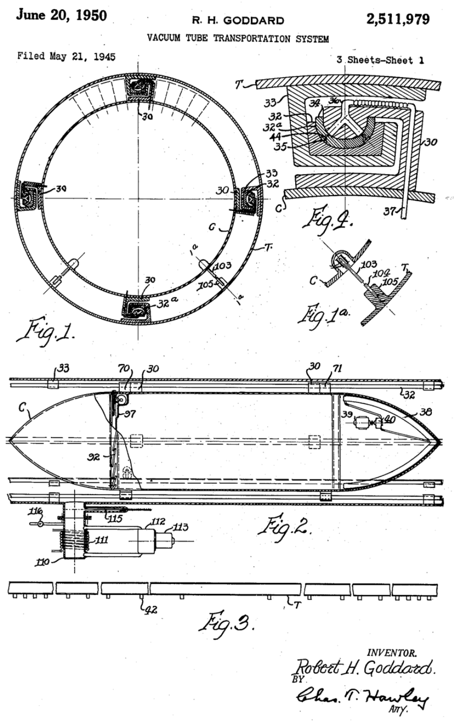


Figure 3 U.S. Patent US2511979A: Transport system for vacuum tubes (Goddard, 1950)

In 1974, the Swiss engineer Rodolphe Nieth developed the so-called Swissmetro, which was also an idea based on air tubes to revolutionize transportation. Along the Swiss Mittelland corridor, the Swissmetro was designed to connect the major cities and guarantee a travel time of a fraction of the current one. For example, the journey time by train from Bern to Zurich takes 1 hour, which can be covered in just 12 minutes with Swissmetro (Förtsch, 2019). The concept involved underground tunnels where air resistance is reduced to 10% of normal atmospheric pressure. As with a maglev train, rolling friction is eliminated as the capsules virtually float in the air thanks to magnetic repulsion. The propulsion works by means of a linear electric motor. However, the project failed due to its highly calculated costs and the lack of support from the government, which focused on expanding the existing railroad infrastructure (Mossi et al., 2023).

Elon Musk reignited interest in tube transportation with his 2013 Hyperloop Alpha concept, intending to create a high-speed, eco-friendly, and economically viable transit system between cities under 1500km apart. Pods would glide through low-pressure tubes on air cushions, driven by a linear electric motor, and primarily powered by solar energy. An open-source approach to development led to the annual Hyperloop Pod Competition. This evolved into a tunneling competition after 2019, while student teams established a similar contest to the one before, the European Hyperloop Week. Commercial entities have since emerged, including Virgin Hyperloop One, shifting its focus from passengers to freight after its initial manned test, and Hardt Hyperloop, introducing lane-switching technology. Several other companies are pursuing alternative technologies, like Inductrack magnetic levitation and MagRail technology for existing rail infrastructures.

## 2.2 A brief overview of the technology

Technologically, the Hyperloop concept is based on three fundamental elements. Firstly, of course, the propulsion, which sets the whole system in motion, keeps it there and can decelerate and break, secondly, the levitation that is needed because the capsules no longer work with wheels at such high speeds, and finally, the condition in the tube, i.e. the vacuum or part vacuum, which reduces air resistance. In the following, the three subsystems are examined in more detail from a technical point of view.

### 2.2.1 Propulsion System

As mentioned above, the propulsion system is concerned with setting the capsules in motion, keeping them at the desired speed during the trip, decelerating and stopping when needed. In doing so, the propulsion system must overcome the moment of inertia and provide a comfortable acceleration and deceleration for the comfort of the passengers. There are two fundamental technical principles. One is the principle based on axial compressors, and the other is the more commonly used principle of linear electric motors (Mitropoulos et al., 2021).

The axial compressor is installed at the nose of the pods and compresses the air in front of it. The air is sucked in at the front and expelled at the rear with higher energy, generating thrust that propels the pods. With such a system, the initial acceleration phase can be considered impractical. This is the technology relied upon by the company mentioned above, Zeleros. The system is more straightforward in theory and more energy efficient. In addition, maintenance costs are said to be kept lower as there is no need to install linear electric motors inside the tube (Förtsch, 2021).

There are three different versions of linear electric motors. The linear induction motor, the linear synchronous motor and the linear switched reluctance motor.

The linear induction motor is a rotary motor consisting of a rotor and a stator, as seen in Figure 4. The stator generates a variable magnetic field utilizing an air gap. In a linear sequence, magnetic conducting poles are attached, which drive time-varying electric currents through the windings to generate time-varying magnetic fields which interact between the pods and the tub (Palka & Woronowicz, 2021).

In the linear synchronous motor, a series of permanent magnets on the pods, together with coils on the tubes, form the foundation. Collectively, a traveling magnetic field is generated along the track by the stator, which is also located on the tube. An excitation system on the pod stimulates the levitation electromagnet, creating an excitation magnetic field. The linear synchronous motor can thus reach high speeds, making it particularly suitable for an energy-efficient Hyperloop (Gieras et al., 2016).

The linear switched reluctance motor operates with interactions of electromagnetic fields and magnetic attraction. Unlike a linear synchronous motor, motion is generated by the attractive force between a moving part, the rotor, and a fixed part, the stator. Thanks to the high energy efficiency potential, the linear switched reluctance motor becomes well suited for a hyperloop system (Garcia-Amoros et al., 2020).

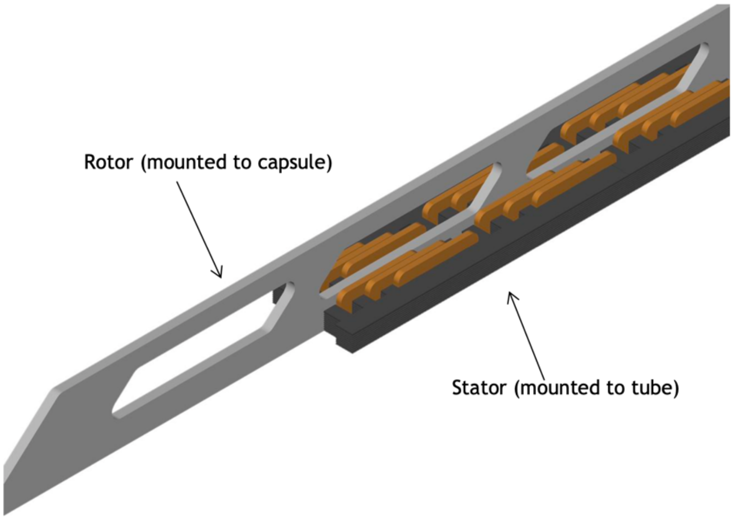


Figure 4 3D Model of a linear induction motor (Rotor and Stator) (Musk, 2013)

### 2.2.2 Levitation

Hyperloop technology is expected to cover distances of more than 1000 km at speeds approaching the speed of sound. To make this possible in the first place, the frictional forces must be made as small as possible. This includes the frictional forces usually generated by the wheels on the rails of a train. In Hyperloop technology, there are currently two approaches to solving this problem, firstly using sliding air bearings and secondly by levitating magnetic suspension systems (Chaidez et al., 2019).
Initially proposed by Elon Musk in Hyperloop Alpha, air bearing involves keeping air under pressure and releasing it through vents. This creates the air cushion on which the weight resting on it, in this case, the pod, causes it to float, as seen in Figure 5. To maintain the air bearings for a long time, a compressor is mounted on the nose of the pods. This draws in the air and compresses it, releasing it under the pod. To operate this compressor and float high enough, a lot of energy in the form of electricity is needed. Furthermore, safety concerns arise because the rapidly rotating compressor is located directly in front of the passenger. Since the compressor is constantly turning, a high level of maintenance is required (Delft Hyperloop, 2019).

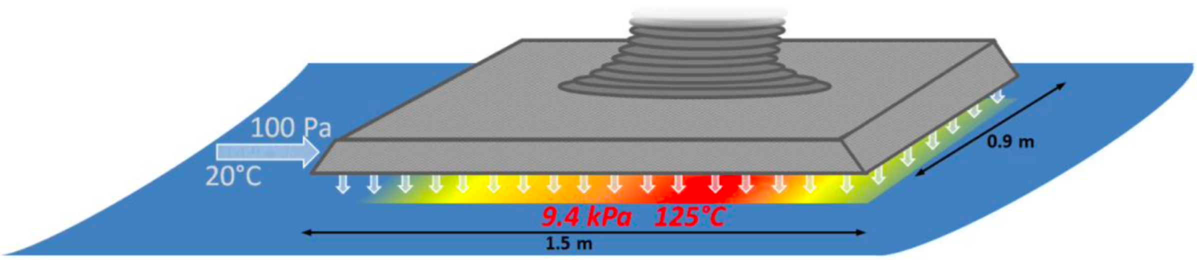


Figure 5 Illustration of air bearings by an air compressor. (Musk, 2013)

Floating magnetic suspension systems are nothing new and have already been used in the Maglev train systems mentioned above. The idea is the same as with the air bearings except that instead of using air to levitate the pod, magnets are used. With electrodynamic suspension, the electromagnetic forces repel each other. In electromagnetic suspension, however, the two electromagnets attract each other, as can be seen in Figure 6. As soon as the distance between the pod and the tube becomes too small, which is continuously measured by sensors, the distance can be reduced or increased by adjusting the strength of the electromagnets (Delft Hyperloop, 2019).

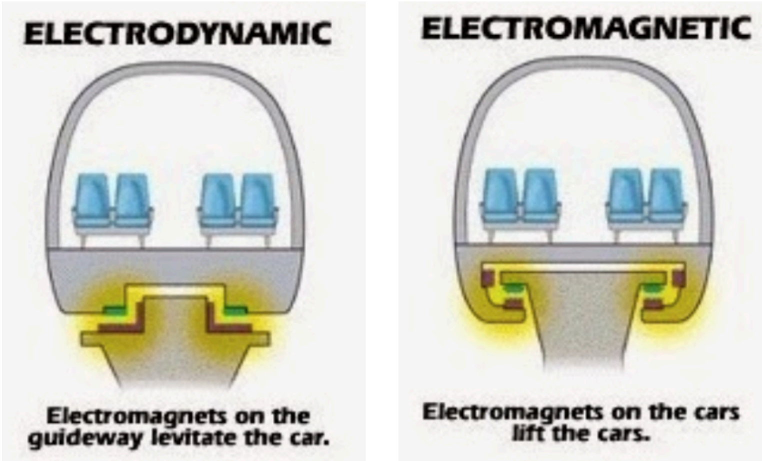


Figure 6 Electrodynamic vs. electromagnetic (Yavuz & Öztürk, 2021)

### 2.2.3 Air resistance

Similar to levitation, the reduction of air resistance in the tube reduces the total drag force to make the high speeds possible and to increase the system's efficiency. Since the air resistance increases as the square of the speed, the power requirement increases with the cube of the speed. This means that to go twice as fast, the pod must overcome four times the air resistance and generate eight times the power. Therefore, reducing the air resistance in the tube makes sense to use less energy and thus become more efficient. Similarly, airplanes fly at an altitude where the air is less dense. The air pressure in the tube of the Hyperloop is reduced to 100 Pa, which reduces the air resistance by 1000 times compared to sea level, which would be the same as an airplane flying at an altitude of 45000 meters, as can be seen in Figure 7. The extreme variant of the complete vacuum may seem attractive at first sight since the air resistance would be eliminated entirely. However, creating a vacuum over a long distance would drive the costs to infinity and would be difficult to maintain. Therefore, low-pressure solutions are preferred (Musk, 2013). Nevertheless, there are still unresolved aerodynamic issues, such as the generation of shock waves when the pods exceed the sonic velocities (Delft Hyperloop, 2019).

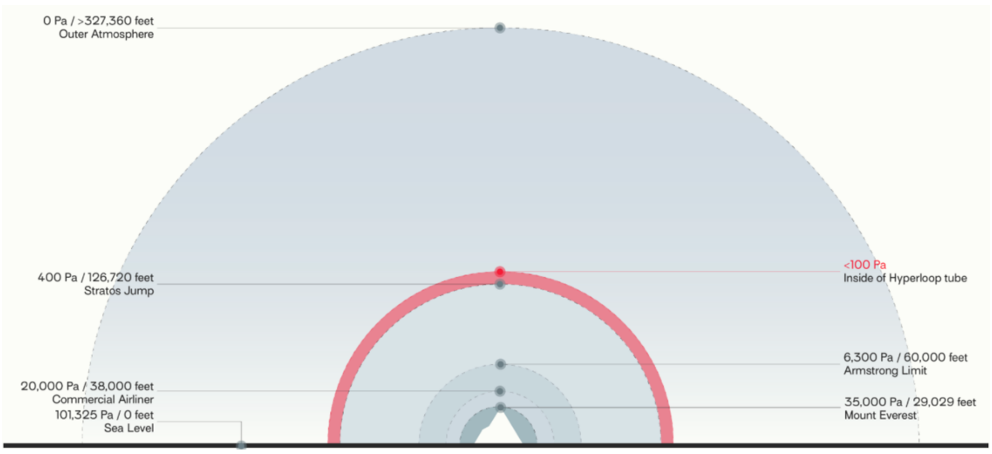


Figure 7 Pressure inside the tube at near vacuum (HyperloopTT, n.d.-b)

## 2.3 Total Cost of Ownership

The total cost of ownership (TCO) is a financial estimate for companies that considers not only the procurement costs but also all costs incurred in the acquisition, operation and disposal of the product or service during its entire service life. Thereby direct costs result as the purchase price or repair costs and indirect costs as downtimes or training courses. The concept of TCO is used by companies and individuals to estimate the full financial value of an investment, making informed decisions about whether to buy or lease a particular asset and comparing the costs of different options over the long term (Hahn & Kaufmann, 2014).

In doing so, TCO relies on the iceberg principle, as seen in Figure 8. According to this principle, around 15 percent of the costs of a product or service are visible, i.e. these are the direct costs. On the other hand, there are the invisible costs, i.e. the indirect costs, which comprise a much larger part of the total costs.

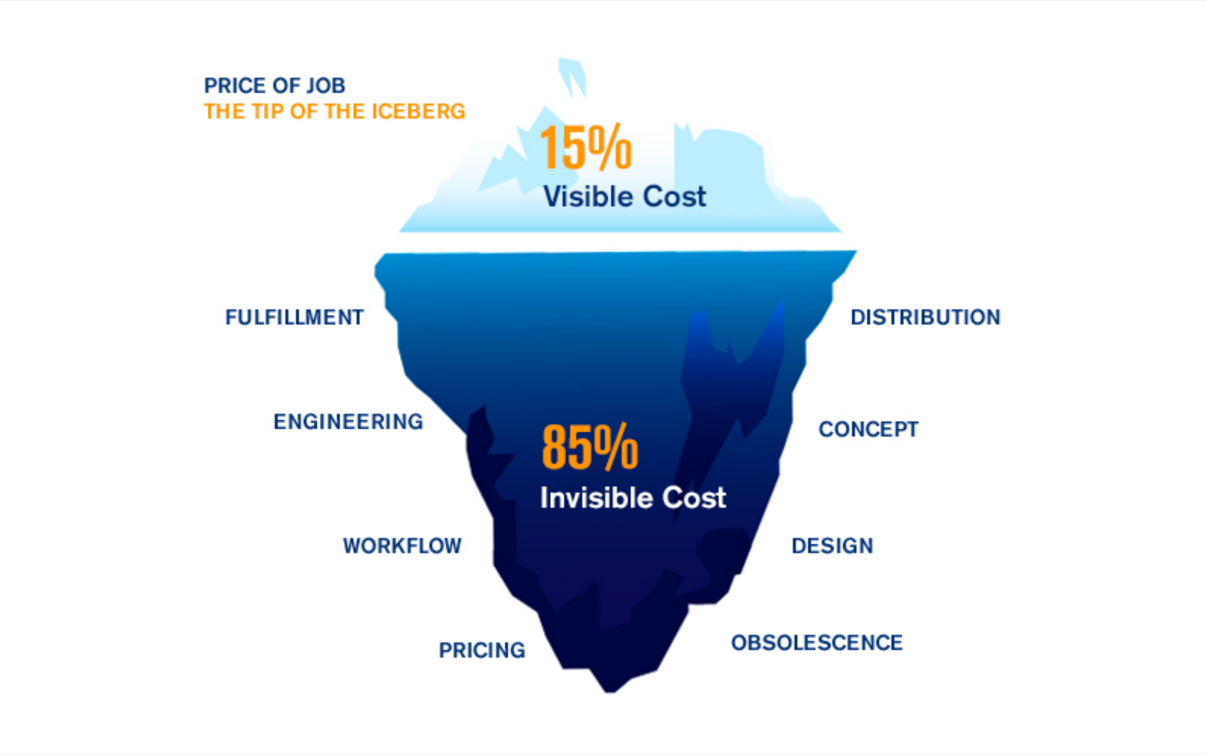


Figure 8 The Iceberg principle of TCO (*Total Cost of Ownership*, n.d.)

Interest in TCO has grown enormously in recent years. Not least thanks to better computer systems, which have made it possible to gain full access to data and analyze it. This was difficult with prior systems. It has also significantly changed the relationships between companies. According to a study, the reduction of TCO is the main reason companies enter into strategic alliances. But TCO also has other effects on the business environment, such as supply base reduction, outsourcing or supply chain management.

Fundamentally, TCO can be divided into three categories. Firstly, the costs and activities that occur before the transaction. These include, for example, the identification of needs or the costs of preparing the contract. Second, the costs and activities that occur during the transaction. These include, for example, the price, transport or return of defective parts. Finally, the costs and activities that occur after the transaction. These include, for example, downtime costs, repairs or disposal.

### 2.3.1 Direct and indirect expenses

As already mentioned, a distinction is made between direct and indirect costs. Direct costs are costs that, as the name suggests, can be directly allocated. This means these costs have a fixed relationship to the product or service, such as material costs, production wages or similar. It is often the case that the relationship between costs and quantity remains the same, but this is not necessarily the rule. More important, however, is the direct causal relationship between the generation of the costs and the production process. In simple terms, the cost causer can be determined directly, i.e. the costs can be allocated without any problems and there is no need for distribution. Indirect costs, on the other hand, are costs that cannot be clearly allocated. These can be administrative costs or training. In order to be able to calculate reasonably, these costs must also be assigned to the product or service in a certain way. In practice, cost centers are defined, i.e. places in the company where these costs are incurred. Thus, the indirect costs for the calculation can be assigned to individual cost centers in the company (*Kosten*, n.d.).

### 2.3.2 The necessity of TCO for Hyperloop

The Hyperloop concept is a large and expensive infrastructure project that involves further costs during the entire life cycle after the initial construction. In the already mentioned white paper Hyperloop Alpha by Elon Musk, a cost calculation was also listed. The costs for constructing the Hyperloop connection from Los Angeles to San Francisco were estimated at between six and seven and a half billion dollars. These are not the complete TCO but only the acquisition/construction costs. Since solar panels will cover the tubes entirely, Elon Musk says the electricity costs will be fully recovered and even a surplus can be fed back into the grid. All other operating costs were neglected in the paper. In addition to other points of criticism, such as technical feasibility, safety concerns, earthquake safety and so forth, the estimated costs were also heavily criticized. For one thing, a single company could not assemble an Hyperloop infrastructure on a simple assembly line like its Teslas; instead, it would require countless different engineers and suppliers, all of whom charge their own profit margins on the subsystems they design and build. The pillars on which the tube will be built have also been criticized, as an Hyperloop connection can only climb or descend a maximum of 10 degrees, making it difficult to mass-produce the pillars. In contrast, each pillar would have to be custom-built, driving up costs. The cost of buying the necessary land was also calculated to low by Elon Musk, as he wanted to build the line along Interstate Highway 5. Nevertheless, costs for land purchase would arise as well as the feasibility would be questioned since the interstate would have to be closed for the construction period (Lavanchy, 2013).

Markus Hecht, a professor at the Institute of Land and Sea Transport at the Technical University of Berlin, is also critical of the Hyperloop concept: "I think the concept is unrealistic. Such projects are hardly financially feasible". He compares the projects with the failed Swissmetro project, discontinued in 2009 for financial reasons (Becker, 2013).

Alexis Madrigal of The Atlantic also sees the cost of the Hyperloop connection as the main problem. Accordingly, Elon Musk estimates the cost of land acquisition at $1 billion. Comparing this to the planned California High-Speed Rail project, which is estimated to cost $7 billion for land acquisition on the route from Fresno to Bakersfield alone, a little over 100 miles, of the total 700 miles, the costing for the Hyperloop connection seems quite optimistic even if it is built along Interstate Highway 5 (Madrigal, 2013).

Although much has happened since 2013 and the white paper on Hyperloop published then, there are still myriad challenges and questions ahead of an actual Hyperloop connection. What is clear, however,

is that Hyperloop represents a tremendous opportunity for the entire global population and would solve many of the current acute problems. Nevertheless, it will probably be a while before people board an Hyperloop capsule in Zurich and cover the distance of around 600 km to Paris after a journey of about 40 minutes. There is no question that such a means of transport would open up completely new possibilities. But until then, more research needs to be done and questions of safety, technical possibilities and route profiles need to be addressed. And as has been shown, one of the biggest obstacles in the path of the Hyperloop still has to be overcome: the question of costs. Projects such as the Swissmetro have failed because of the costs. Therefore, it is essential to know the total cost of an Hyperloop connection, including the initial construction costs as well as the subsequent operating costs over the lifetime of the infrastructure. No investment, certainly not on the scale of an Hyperloop, will be made unless it can be based on a sensibly listed cost calculation.
For this reason, this report deals with the modeling of an Hyperloop connection from Zurich to Paris with the aim to include all essential cost points in the calculation and to ensure a comprehensive insight into the costs of a future realized Hyperloop connection as well as assumptions about to what certainty the costs can be predicted with the information available and what are the parameters with the most influence on the operational costs.

## 2.4 Interim conclusion

The previous chapter of the foundations has been concerned with deriving the basic idea of the Hyperloop concept. The first ideas and concepts were discussed and gradually, the history up to the modern concept of the Hyperloop Alpha was worked through. The importance of Elon Musk's white paper published in 2013 and the technology behind and how it works was explained and more detail was given on the main components, propulsion, levitation and vacuum. The conclusion of the chapter describes the total cost of ownership approach, what is behind it and why knowledge of the cost of an Hyperloop connection is of fundamental importance. All in all, this results in the fundamental chapter that forms the basis for the further procedure in this report. To date, no full cost accounting of an Hyperloop connection is available. Previous attempts, like Elon Musk's white paper, have been criticized for the vaguely estimated costs. For further research and the realization of the Hyperloop system, not only the technical aspects are important, but also the economic ones. For these reasons, this report focuses on modeling the costs of a hypothetical Hyperloop connection to determine not only the investment costs and operating costs of such a connection but also to make well-founded statements about necessary future research and to identify cost factors that drive up the costs.

# 3 Methodology

The methodology chapter is a fundamental part of any research project, as it describes the procedure for answering the research questions. In doing so, it ensures the comprehensibility of the resulting findings and the reproducibility of the research work. This report is concerned with developing a fully detailed cost model of an Hyperloop connection from Zurich to Paris. In Figure 9, a rough overview of the methods used can be seen. The following chapter presents the methods, tools and techniques used to collect and analyze the data underlying the research results. The purpose is to provide a thorough and detailed explanation of the research process, including the strategies used to plan the research, create the scenario, develop the cost model, collect the data, simulate, and analyze the results. The methodologies used in this report are described, along with the limitations, strengths, and weaknesses. In addition, the reasoning behind the choice of methods is disclosed and a clear description of what results are hoped to be achieved by each methodology is provided. In this way, this chapter aims to increase this research's transparency and reproducibility and help evaluate the validity and reliability of the results.

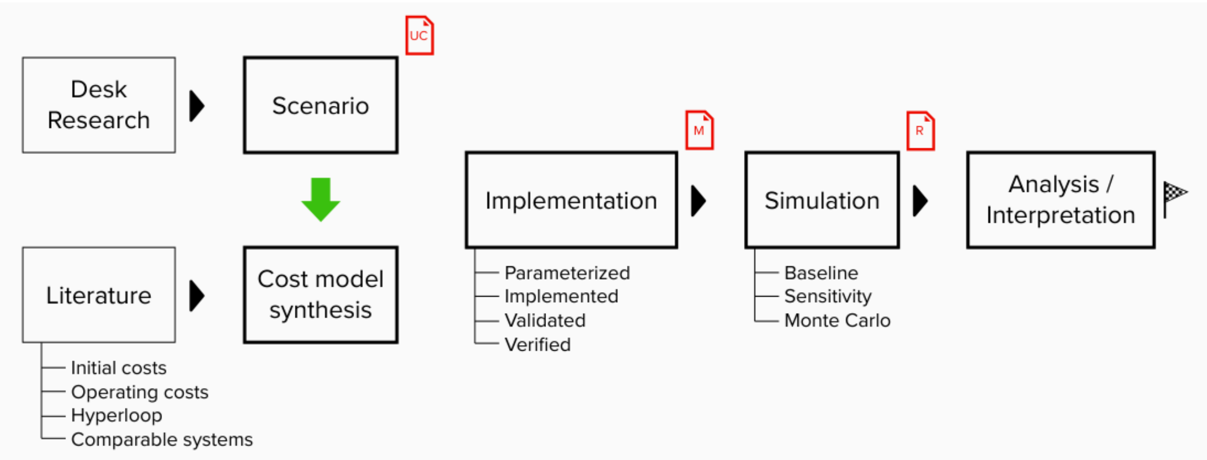


Figure 9 Methodology Overview

## 3.1 Scenario

The fundamental scenario for the Hyperloop connection from Zurich to Paris was created with literature research. This part of the work aims to describe the hypothetical route in detail to evaluate the costs later. Mainly the state of the art of corresponding companies, start-ups and research groups in the Hyperloop field was used. First, a qualitative approach was chosen to gather all possible information. Afterward, the most suitable variant was selected qualitatively. Wherever too little information was available, assumptions were made. The methodology comprises the following steps:

- *Identification of the relevant literature.* In this step, all relevant existing literature in the field of hyperloop was reviewed. Various academic databases, research journals, conference proceedings, and relevant industry reports are searched to identify scholarly articles, research papers, and case studies. The keywords used for the literature search include "hyperloop system," "hyperloop scenario," "hyperloop feasibility study" and related terms.
- *Selection of literature.* After gathering the most critical literature related to the development of the Hyperloop connection scenario, the next step was to select the relevant information. The screening process includes assessing each article's title, abstract, and keywords to determine their relevance to the research topic. The criterion for the decision was the

consistency of the information with the research objective of this work. Exclusion criteria may include outdated studies, irrelevant topics, and publications lacking empirical data. However, due to a lack of literature in the area of the Hyperloop concept, the broadest possible range was considered.

- *Data Extraction and Analysis.* Once the relevant source had been identified, the task was to extract and summarize the essential information for the development of the scenario. All required information for the development of the scenario was collected. This was always done with a view to modeling the costs. Unessential definitions with no impact on costs were omitted. The collected data is then organized and analyzed to identify patterns, trends, and relationships among the Hyperloop concepts.
- *Scenario development.* The scenario development phase involves the construction of a hypothetical case based on the literature analyzed. This step requires synthesizing the information from the literature review, considering the cost factors identified, and incorporating relevant assumptions and variables. The scenario is designed to be a realistic representation of an Hyperloop system, taking into account geographic location, route length, passengers, energy sources and other relevant factors. Later sensitivity analyses can be used to assess the impact of varying parameters on overall costs.
- *Review of the scenario.* To check the scenario for accuracy, it was compared with existing concepts and prototypes. Furthermore, a discussion was held with an industry insider about the developed scenario. Any necessary adjustments are made based on the obtained feedback to improve the scenario's robustness and alignment with practical considerations.
- *Limitations.* The chosen methodology includes some limitations, which are noted below. Restrictions may include the availability and quality of the literature, potential biases in the selected studies, and assumptions made during the scenario development. Especially since the Hyperloop concept is mostly theoretical concepts and prototypes and there is no real-life track.

## 3.2 Cost model

To develop the cost model of an Hyperloop connection, secondary data collection was used. This was done through desk research, a method in which existing knowledge and information from previous studies and research is used to gather information about the current research project (Stewart & Kamins, 1993). The process can be considered identical to the previous section.

The first step was to collect the most essential sources related to cost models in the Hyperloop field or related fields such as the railway industry. In the next step, these sources were screened and the most relevant ones were selected. Subsequently, the essential data was extracted from the sources and analyzed. Finally, the cost model for the Hyperloop system was established. Existing cost model calculations from the literature and similar systems were used and combined with the information about Hyperloop to form a common cost model of the Hyperloop technology. Qualitative data was collected from various sources from papers, studies, textbooks, articles and the like. Relevant search terms were determined and systematically searched for in the abstracts. In case of overlaps, the available material was skimmed and the important sections were studied in more detail and compiled. In the end, a typical cost model from the railway industry was chosen, which has already been used as the basis for several Hyperloop studies. This was adapted according to the scenario. The same limitations as described above also apply in this section.

## 3.3 Implementation

After the scenario for the Hyperloop connection from Zurich to Paris has been set up and a suitable cost model for such a scenario has been developed, the next step is the parameterization. This involves filling the cost model with the appropriate parameters. Parameterization in cost modeling means identifying the specific cost factors that matter and quantifying these factors to build the cost model. This can include identifying direct and indirect costs, fixed and variable costs, and other specific cost drivers. Parameterization is an important step in modeling costs and financial data because it quantifies the relevant parameters to produce more accurate forecasts. A well-parameterized model can help improve decision-making and enhance the understanding of a business's financial situation. The parameters should therefore ultimately be implemented in the model, i.e. the quantified variables are introduced into the cost model and configured so that the model works with the correct input variables.

A literature search was also used for this purpose. The process can again be modified from the one already described. The collected literature from the scenario and the cost model served as a solid foundation for the parameterization. For all other parameters, additional literature was collected and then, after a review, the useful ones were selected and analyzed. This process led to parameterizing the cost model with all the associated cost centers specified whenever necessary within the framework. This, on the one hand, since the costs are afflicted with a particular uncertainty and, on the other hand, to simulate the influences of the cost centers in the sensitivity analysis. Also, here it is important to mention again the limitations. These include the availability and quality of the available sources, potential biases, and assumptions made due to lack of information. There are gaps, especially in the area of costs, as a commercial connection has never been realized.

In summary, this step deals with the elaboration of the parameters. These parameters are then implemented into the already developed cost model and the implemented cost model is finally checked to ensure that the model can be further processed.

## 3.4 Simulation

Once the cost model has been parameterized, implemented and tested, simulations can be performed. A simulation is a replication of a real system or process on a computer system or other artificial environment. Such one is used to model and analyze the behavior of the real system under various conditions without affecting the real system itself. Simulation models may contain parameters and variables that reflect the conditions and circumstances of a real system. The results of a simulation can be used to make predictions about how the system would behave in the real world under various conditions (Ingalls, 2011). In this specific case, a simulation of the operating costs of an Hyperloop connection is made, where the parameters reflect the circumstances of a real system and the results obtained can be used as a prediction of how such a connection can be realized in reality, in terms of costs.

In the first step, a baseline simulation is performed, which is a simulation that serves as a basis for further simulations. It is an initial version used as a starting point for the development of alternative variations and aims to answer the question of the expected operating costs of an Hyperloop connection.

In the second step, a sensitivity analysis is performed (Borgonovo, 2017). This is a method for evaluating the impact of changes to a system's input parameters or variables on the output results of a simulation or modeling. It helps identify the most critical factors affecting the behavior of the system. A sensitivity analysis typically involves running multiple simulations, varying one or more parameters

at a time. The results of these simulations are then compared to determine which parameters impact the system most. Such an analysis is useful when the input parameters to a system are uncertain or when there are many different input parameters. This is the case in the Hyperloop connection, many parameters are estimated or assumed. Therefore, such a sensitivity analysis is performed. The goal is to finally determine the parameters that have the most significant influence on the costs. These sensitivities indicate which parameters should be considered for cost reduction and where there is still a need for research in the future.
The third and final step is a Monte Carlo simulation. A Monte Carlo simulation is a simulation based on the generation of random numbers to model the possible outcomes of a system or process (Mooney, 1997). The process consists of generating a large number of random numbers that are used as input parameters to the model. The simulation then calculates the model results for each set of random numbers. The question to what certainty the costs can be predicted with the information available and prediction will be presented to discuss the expected certainties of operational cost predictions at the current stage.

### 3.5 Approach for modeling and simulation according to Acél

The procedure described above for modeling the operating costs of an Hyperloop connection from Zurich to Paris and thus also the achievement of the objectives of this report can be compared with the procedure methodology for modeling and simulation according to Acél (Acél, 1996). Acél presents a systematic and goal-oriented methodology, which is divided into four sub-steps and comprises a total of 14 steps, as can be seen in Figure 10. The steps include the definition of the application, model building, simulation and solution recommendation. The first step of the mission definition deals with the definition of the current situation and the goal of the simulation. It is covered in this report with the development of the scenario. The second step of model building includes the model conception and data collection as well as verification and validation of the model, which is covered by the steps of cost model synthesis and implementation. In the third sub-step, according to Acél, the simulation, as the name implies, the Simulation is carried out in different variants. The interpretation and analysis of the results is treated in this report as a separate chapter. The last sub-step of the solution recommendation is the complete documentation, which happens simultaneously in this report. Overall, this report follows Acél's proposed structure and the individual steps can be compared with the procedural methodology.

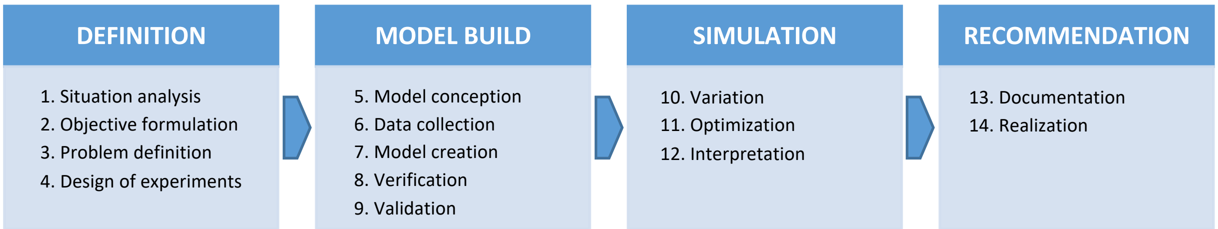


Figure 10 Approach for modeling and simulation according to Acél

## 4 Scenario definition

This chapter is about the definition of the scenario of the Hyperloop connection from Zurich to Paris. It defines and describes the fundamental basis of the connection and includes the route, the capsules and the stations. Furthermore, all relevant definitions are made to carry out the simulation of the costs in the further course of the report. The scenario serves as an intermediate outcome on the way to the final result. Accordingly, the creation of the scenario is of great importance. The definitions are always based on existing knowledge, if this is not available, quantitative estimates are made, and if this is also not possible, assumptions are taken. All information of the scenario, which cannot be determined unambiguously, is indicated within a range. This is not a disadvantage, but a chance in the later simulation, especially in the Monte Carlo simulation, to make well-founded statements about the parameters. An overview of the scenario can be seen in Figure 11.

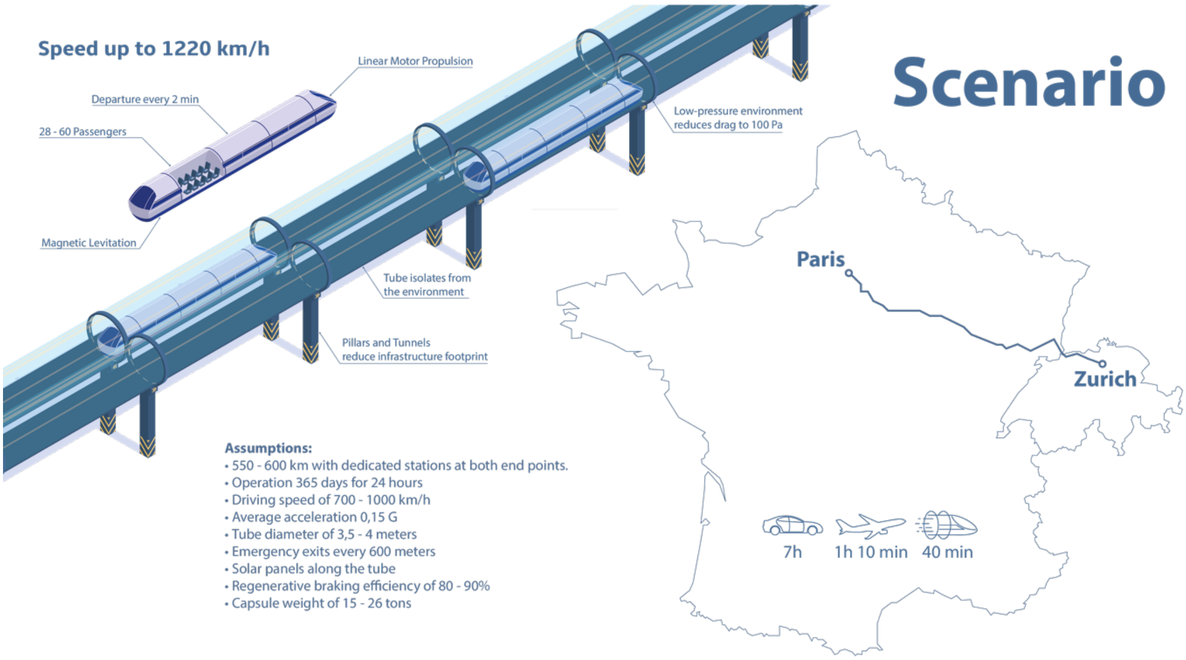


Figure 11 Overview of the Hyperloop scenario from Zurich to Paris

### 4.1 Definitions

An Hyperloop connection can basically be used for passenger or freight transport. The Virgin Hyperloop One company initially focused on transporting people and was also the first company to carry out a manned test run. However, the company announced a change in strategy at the beginning of 2022 and will focus on the transport of goods from now on. The reasons for this are not precisely known. On the one hand, the strategy change is said to have been driven by the high demand for freight transport caused by the Corona pandemic. On the other hand, there are still many unanswered questions, especially in the area of safety, when it comes to transporting people (Holland, 2022).

The alignment is not much different in terms of infrastructure. The only difference is in the capsules. However, this is not in the sense of the drives or the geometry, but merely that the capsules do not have seats for freight transport. Therefore, for the fundamental scenario, whether freight or passenger traffic does not matter much. However, for the sake of simplicity, the system is limited to the transport of passengers.

It is assumed that the Hyperloop connection will be in use 365 days a year, 24 hours a day. According to Hyperloop Alpha (Musk, 2013) and Transpod (Transpod, 2017), there is an average time interval of two minutes between the departures of the individual capsules. Elon Musk assumed a maximum speed of 1220 km/h (Musk, 2013). This is also confirmed by HyperloopTT, with a top speed of 1223km/h (HyperloopTT, n.d.). Transpod and Hardt assume a maximum speed of 1000km/h (Transpod, n.d.). However, a distinction can also be made between maximum and cruising speeds. Hardt, for example, puts it at 700km/h (Hardt Hyperloop, n.d.). Elon Musk assumed different speeds. On the one hand, the top speed of 1220km/h and on the other hand, a speed of 480km/h in hilly and curved areas (Musk, 2013). Since curves and hills have already been considered in the route, a cruising speed of 700 - 1000 km/h is assumed in this scenario. Only during acceleration and braking is the speed lower. It is assumed that the speed is accelerated once to the cruising speed, which is maintained during the entire journey and is only decelerated again at the end. The assumptions also differ when it comes to acceleration. Elon Musk limits the maximum acceleration to 1G for maximum comfort (Musk, 2013). HyperloopTT (HyperloopTT, n.d.), on the other hand, only talks about 0.1G acceleration and Hardt assumes around 0.15G (Hardt Hyperloop, n.d.). According to a study by van Goeverden, the acceleration is 0.5G (van Goeverden et al., 2018). The acceleration of modern suburban and metro trains is about 0.13G (Wikipedia, 2023). Therefore, an average acceleration of 0.15G is assumed in this scenario.

## 4.2 Stations

At the two endpoints in Zurich and Paris, a new station will be built explicitly for the Hyperloop connection. This station is to be located in the center of the cities. Both stations have arrival halls for the tubes. Since there is a vacuum in the tubes, three chambers are needed. In the first chamber, the capsules arrive and the pressure is equalized to the ambient pressure. In the next chamber, the passengers are loaded and unloaded and finally, in the third and last chamber, a vacuum is created again and the capsules start their journey (van Goeverden et al., 2018).

The stations are strategically placed centrally in the cities to ensure that the stations can be reached quickly and easily and are not located outside the city, like most conventional airports. Therefore, a large part of the costs is related to land acquisition. Prices per square meter in major cities such as Zurich and Paris are expensive, driving up the cost of the stations.
The resulting area of the stations can, however, be used and covered with solar panels to supply the station itself with electricity. If there is any excess, it can be used directly to power the capsules.

## 4.3 Track

The route planning of an Hyperloop connection is complex and is therefore not carried out in detail. Among other things, it must be taken into account that only large curve radii are possible at high speeds. The same applies to the gradients. Hardt assumes a minimum curve radius of 200 meters and a maximum rise or descent of 10 degrees (Hardt Hyperloop, n.d.). Alternatively, smaller curves and larger inclines can be overcome, but not at higher speeds. Due to these restrictions, there is no way around building a part below ground or in tunnels. The distance by air between Zurich and Paris is about 490km. The distance by car is about 600km (Google Maps, n.d.). Since it is rather unlikely that the Hyperloop connection will be able to follow the straight line, the scenario assumes a distance of 550 - 600 kilometers. The route between Zurich and Paris is relatively flat, yet the cities have an altitude difference of 373 meters. Over 600 kilometers, this results in an average gradient of 0.06 degrees. However, since the line is not all straight, this report assumes that the route runs in tunnels and on pillars of different heights. Different distributions are considered; 25% tunnel and 75% pillars, 50% tunnel and 50% pillars and finally 75% tunnel and 25% pillars. Elon Musk defined the distance between the piers as 30 meters (Musk, 2013). Transpod assumes 25 meters (Transpod, 2017). This report will therefore settle on a pier spacing between 25 and 30 meters.

The vacuum is generated with pumps. In Musk's original idea, the pumps are only installed at the stations (Musk, 2013). However, it is not entirely clear whether this is sufficient for the vacuum on the entire route. According to estimates from Swissloop and Transpod, more pumps are needed along the way to maintain the partial vacuum (Kalrav, 2019). HyperloopTT assumes pumps every 10 kilometers (HyperloopTT, n.d.). Therefore, this scenario assumes that a vacuum pump will be installed every 10 kilometers. These vacuum pumps guarantee a pressure inside the tube of 100 Pa, about one-thousandth of the ambient pressure at sea level.

Two tubes are built parallel to each other so that the connection can be used for two lanes of traffic. The tube itself is made of steel and mass-produced. The individual sections can be connected to each other and the two tubes are laid parallel. The diameter of the tube was estimated by Elon Musk at 2.23 meters (Musk, 2013), according to other sources, for example Hardt, the diameter is significantly larger at 3.5 meters (Hardt Hyperloop, n.d.). HyperloopTT (HyperloopTT, n.d.) and Transpod (Transpod, 2017) both even assume a diameter of 4 meters. Since the capsules should offer more space and be comfortable, a diameter of 3.5 - 4 meters is assumed.

The emergency concept is an often forgotten but nevertheless crucial element of an Hyperloop connection. This was also neglected by Elon Musk in the Hyperloop Alpha and later criticized. There is no concrete emergency concept yet, as no Hyperloop system has been realized yet. Therefore, this scenario is limited to emergency exits along the Hyperloop connection. In a paper by Transpod, an emergency exit is installed along the route every 600 meters (Transpod, 2017). These can already be prefabricated in the tubes. This would result in about 1000 emergency exits per line from Zurich to Paris.

There is no need for conventional rails in the tube for the capsules. The original idea of Elon Musk (Musk, 2013) and Hyperloop One (Kalrav, 2019) was that the capsules are supported via air bearings that operate using a compressed air reservoir and aerodynamic lift. However, this idea has been dropped further down the line. Most current concepts envisage electromagnetic levitation of the capsules (Hardt Hyperloop, n.d.), as explained in the Fundamentals chapter. Therefore, in this scenario, the capsules float electromagnetically in the tubes. This also means that there is no friction and wear can be minimized.

The resulting surface area on the tubes can be used to generate solar energy. Elon Musk believed that the electricity generated would be enough to power the system and even feed a residual into the grid on extremely sunny days (Musk, 2013). However, another study believes the generated energy will not be enough to keep the complete system running (Kalrav, 2019). Nevertheless, a significant part of the energy can be generated by the system itself. Therefore, also in this scenario, the surface of the tubes is covered with solar panels, of course, only during the sections that are not in a tunnel. The diameter of the tubes is set at 3.5 - 4 meters and the distance that will be covered varies depending on the length of the open pit and the total distance. The maximum length of the line is 600 kilometers and 75% open pit. This gives a distance of 450 kilometers, which can be built over.

A major cost factor for such an infrastructure project is the land acquisition. A large land area must be purchased to build the stations and the line. For this report, different assumptions are made, one being that 100% of the land of the line must be purchased, i.e. not yet owned by the government, and the other 50%. If we calculate with a buildable area of 30 meters, we need a maximum area of 18'000'000 square meters and a minimum of 8'250'000, taking into account that about 80% of the line runs through France and 20% through Switzerland.

## 4.4 Capsule

The number of seats in a pod differs between different studies. Elon Musk's Hyperloop Alpha talked about 28 people per pod (Musk, 2013). Hardt Hyperloop (Hardt Hyperloop, n.d.) speaks of capsules with space for up to 60 passengers and HyperloopTT estimates the capacity between 28 to 48 occupants (HyperloopTT, n.d.). Transpod's concept includes 54 people plus two wheelchair spaces (Transpod, n.d.). So the numbers vary roughly between 28 and 60 seats. The present scenario, therefore also assumes a capacity of 28 to 60 people per capsule.

The drive is provided by a linear motor, as already explained in the basics chapter. The stator is attached to the tube and the rotor to the capsule itself. During acceleration and braking, the stator must be continuously attached to the tube. In a complete vacuum without friction, no new drive would be needed on the way, but since this is not feasible, a new drive, i.e. a stator on the tube, is required at specific intervals. These stators will be placed 112 kilometers apart in the rest of the tube, based on Hyperloop Alpha's estimate (Musk, 2013). According to Hardt, the motor will be continuous throughout the entire route. The electric motor propels the vehicle to its cruise speed. Afterward, it only requires a fraction of the energy to maintain (Hardt Hyperloop, n.d.). This report assumes that the motor will be installed in the tube throughout the entire route.

The capsules have a regenerative braking system, which stores the energy generated during braking and can be used again for propulsion. It is assumed that the efficiency of regenerative braking is around 80% - 90% (Department of Energy, 2021; Siefkes, 2021).

As already defined, the capsule comprises space for 28 - 60 people. The pods do not have toilets; the relatively short duration of the journey means that passengers are asked to empty themselves at the stations before the journey. The seats all have an entertainment system comparable to those found on airplanes. All seats and equipment are identical; no first or second classes exist.
The total weight of the capsules, with a capacity of 28 people, was estimated by Elon Musk in the Hyperloop Alpha paper at 15000 kilograms (Musk, 2013). However, it was criticized that the average weight of a person with 80 kilograms was estimated as somewhat low. According to another study, the weight of a 30-person capsule is estimated at 15560 kilograms. The same study estimates that a capsule for 60 people weighs around 26000 kilograms (Kowal et al., 2022). Since the number of passengers is between 28 and 60 in this scenario, a weight between 15 and 26 tons is assumed. The estimates assume an average passenger weight of 88 kilograms plus a luggage weight of 17 kilograms.

The travel time is about 40 minutes. To guarantee the capacity of capsules every 2 minutes, at least 20 capsules per tube are needed. Since the tubes still spend time in the stations, the number is closer to 25 capsules per tube, i.e. 50 in total. Assuming that the capsules need regular maintenance and that there are failures and repairs, even more capsules are needed. Furthermore, the start time can be shortened when the capacity is high. For example, during rush hour, the capsules could depart every minute. This assumes that twice as many capsules are available. The scenario assumes that between 75 - 100 capsules are available. This way, the average demand of 20 capsules per tube, including failures can be covered and in addition about one-third of additional capsules are available to maximize the operation during rush hours.

### 4.5 Interim conclusion

The previous chapter deals with the establishment of the scenario of the Hyperloop connection from Zurich to Paris. Due to time constraints, the planning was carried out as precisely as necessary, but not down to the last detail. It should be noted that the more detailed the connection is defined, the more accurate the cost planning will be. The scenario, however, is based on the concepts of the leading research and companies in the field of Hyperloop. The ranges were chosen accordingly and left various concepts open. There are overlapping trends in the individual subsystems of the Hyperloop concept, but the technology is still in research and development. Therefore, the scenario is based on the current state of research, which may change in the coming years.

# 5 Cost model

This chapter deals with the development of the cost model. A complete cost model is derived, consisting of the capital costs of the infrastructure and the subsequent recurring operating expenses. The operating costs are again subdivided into fixed and variable costs. Once the cost model has been developed, the appropriate positions are parameterized. To do this, secondary research is again conducted where possible, and if this is not available, primary research is applied. The ultimate goal is to have a comprehensive and parameterized cost model that describes the costs of an Hyperloop connection and forms the basis for the simulation of the costs that will be performed in the next step. All costs are in 2023 US dollars and have been converted to this currency from original studies.

## 5.1 Capital Costs

Capital costs are defined as fixed, one-time expenses. They include expenditures for acquiring land, buildings, structures, and equipment used to produce goods or provide services. In other words, it is the total cost required to bring a project to an operational state (Wikipedia, 2018). In the case of an Hyperloop connection, these are all costs incurred for the construction of the infrastructure to make the connection operational. Roughly speaking, these costs can be divided into three areas of stations, track and vehicles. In addition, costs for Professional Services and Contingency are included. An overview of the capital costs can be seen in Figure 12.

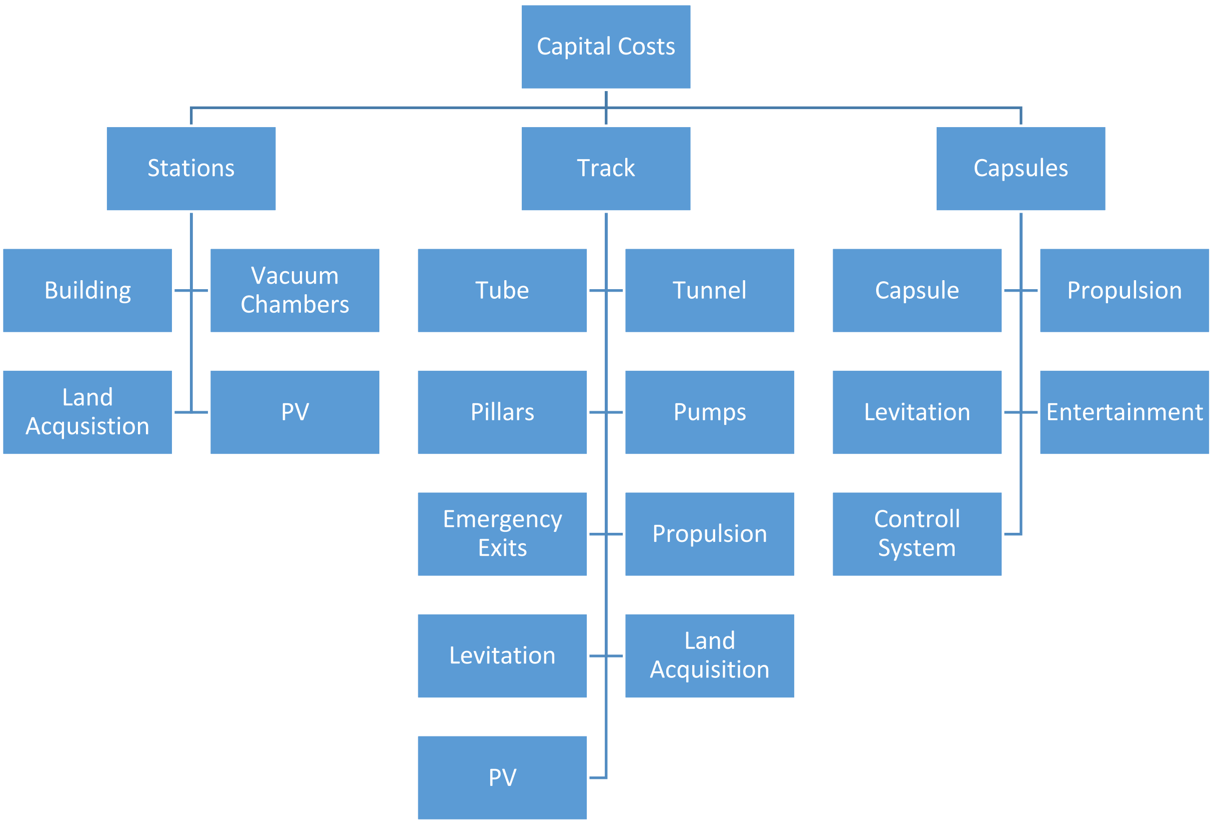


Figure 12 Overview of the capital costs

### 5.1.1 Stations Costs

The stations consist of a building in the center of the cities. From there, the two Tubes start or end. The buildings can be compared to conventional train stations. The difference is that the vehicles cannot simply depart as with trains, but the partial vacuum must first be provided. For this purpose, as described in the scenario, different chambers are used, which are closed airtight and the vehicles are thus reintroduced into the partial vacuum tube. The area on the roof is used to produce solar power. Another significant cost is the land acquisition to enable the construction of the stations. So the cost of the stations can be further divided into building, land acquisition, vacuum chamber and PV system.

According to AECOM, one of the most comprehensive Hyperloop feasibility studies, the cost of two large Hyperloop stations, including civil, structural, architectural work, a provision for Hyperloop-specific station equipment such as pod bays, chargers, compressors, etc. and a contingency of 30% is $467.14 million per station. Together, this would result in a total cost of $934.28 million (AECOM, 2020).
The cost, of course, depends mainly on the station's scope. Is it only a small construction or an airport-like large-scale construction? Elon Musk estimated the cost to be less. According to him, the cost per station is $162.36 million, corresponding to a total of $324.72 million (Musk, 2013). Similarly, another study compares costs to a Shanghai Maglev railroad project, costing $150 million per station (van Goeverden et al., 2018).
If the costs are compared with a modern construction project of a train station, such as the planned long-distance train station in Hamburg, the costs do not differ significantly. The total project is estimated at $680 million. However, it must be mentioned that the construction of the station is planned at $150 million. The rest of the costs are for new tracks and platforms. Therefore, the cost of the station alone at $150 million is closer to the second two estimates (Wikipedia, 2023).
It is assumed in the following that the cost per station is between $130 and $180 million, which comes to a total of $260 to $360 million.

In the center of Zurich, the current average price per square meter is about $7800 (Stadt Zürich, n.d.). On the other hand, the square meter prices for land are unknown in the city of Paris. The real estate prices per square meter, however, are around $14000, about the same as in Zurich (Wikipedia, 2023). Since the real estate prices for both are around $14000 and the land price in Zurich is around $7800, a roughly equal land price can be assumed for Paris. Therefore, this report assumes a price per square meter of $8000 to $9000.
The station building in Zurich has an area of about 16000 square meters. The Gare de Lyon station in Paris also has an area of around 16,000 square meters (Google Maps, n.d.). Therefore, the area of the station building is calculated from 16000 to 20000 square meters.
The price for the land acquisition is therefore, between $252.8 and $336 million.

The Hyperloop system operates in a near-vacuum environment. Therefore, it is essential to guarantee safe boarding and deboarding for passengers. For this purpose, there are various ways in which chambers can be used to equalize the pressure and thus make loading and unloading possible. Delft Hyperloop has presented several such possibilities in a paper and calculated the costs (Delft Hyperloop, 2021). These are between $4.84 and $17 million, depending on the system. The expenses include several platforms. Therefore, this report assumes the same costs per station, resulting in a total of $9.68 to $34 million.

The price per square meter for photovoltaic systems, including all related components, is between $280 and $335 (Beckmann, n.d.). If this is calculated for the area of the stations, the total is between $8.96 and $13.4 million.

### 5.1.2 Track Costs

The track consists mainly of two tubes, which are laid in parallel. These are installed according to the scenario on support pillars or in tunnels. In addition to these costs, there are also emergency exits and vacuum pumps along the route. To build the track at all, the land acquisition costs, as for the stations, are added and the visible sections are covered with PV systems to generate electricity for the operation of the line. Finally, there are costs for the propulsion and the magnetic levitation of the vehicles.

The cost of the tube depends on the diameter and the material. The scenario defined the diameter as 3.5 to 4 meters and the material as steel. According to a study by Delft Hyperloop, the price of the tube per kilometer is $25.55 million, with a diameter of 3.55 meters (Kalrav, 2019). Elon Musk assumed a diameter of 3.3 meters and a total cost of $1.56 billion (Musk, 2013). Calculated on the kilometer, this corresponds to a price of $2.7 million, about one-tenth of Delft’s estimate. According to another estimate by Delft Hyperloop, the steel tube costs around $17.42 million per kilometer, including construction costs, for two tubes in parallel (Delft Hyperloop, 2019). That is about $9 million per kilometer. The figures vary between $3 and $25 million. It is not always clear precisely what is included in these cost estimates. Since this estimate is only for the steel tube, a price of $10 to $15 million per kilometer is assumed. This leads to a total cost of $5.5 to $9 billion for the tubes.

The cost of the support pillars depends on the number. Delft Hyperloop estimates the cost per kilometer for the support pillars at $0.42 million, but it is unclear how far the distance between the pillars is (Kalrav, 2019). In Elon Musk's estimate, the price of the support piers per kilometer is around $7.2 million with a distance of 30 meters between the piers (Musk, 2013). Due to a lack of precise information, a price of $4 to $8 million per kilometer is assumed. This results in a total of $550 million to $3.6 billion.

According to a study by Delft Hyperloop, building a tunnel with a diameter of 3.5 meters would cost around $32.5 million per kilometer for a double-track line (Delft Hyperloop, 2019). Compared to the cost of the Gotthard tunnel in Switzerland, with costs of $260 million per kilometer for two parallel tunnels, the $32.5 million is much lower (van Goeverden et al., 2018). It should be noted, however, that the diameter of the Gotthard tunnel is about twice that of an Hyperloop. According to another study, a two-lane Hyperloop tunnel per kilometer costs $91 million (van Goeverden et al., 2018). Since the tube has already been calculated separately, the price is reduced to around $70 to $80 million per kilometer. This would cause a total cost of $9.625 to $36 billion.

Emergency exits are placed every 600 meters. This requirement came from a report by Transpod. The same report also lists a detailed cost view of the emergency exits. Per kilometer for a double tube, the emergency exits cost $1.85 million (Transpod, 2017). Therefore, for lack of comparative estimates, this amount is assumed for this report. Total costs of $1.0175 to $1.11 billion are incurred for the emergency exits.

In the scenario, it was defined that a vacuum pump is stationed every 10 kilometers. This results in a number of 55 to 60 pumps per tube and thus, a total number of 110 to 120 pumps. According to HyperLoopDesign, a single suitable vacuum pump costs $75,000 (HyperLoopDesign, n.d.). Multiplying this cost by the number of pumps results in a total cost of $8.25 to $9 million. The pumps can be mounted in the already installed emergency exits, so there is no need for additional infrastructure.

The Right of Way describes the right of railroads to use a specific route to build a railroad. In doing so, of course, the owner must be paid. The cost of land purchases and the Right of Way make up a significant part of the cost. Elon Musk has therefore proposed to align the route as long as possible with existing routes, such as highways, since no land has to be purchased there. Nevertheless, he estimates the cost of the line at $1.3 billion (Musk, 2013). Another study estimates the price of a 30-meter-wide track at $110 per kilometer in rural areas and $330 in urban areas (Transportation Economics & Management Systems, Inc., 2010). As defined in the scenario, the maximum area is 18,000,000 square meters and the minimum is 8,250,000. The average price per square meter in Switzerland is around $900 (hausinfo, 2022). In France, there are no exact figures, but the average cost should be somewhat lower. Therefore, an average price of $600 per square meter is assumed. This results in a total price of $11.88 billion if the entire land has to be purchased and $5.445 billion minimally.

For the photovoltaic system, the price per square meter is used again, including all related components, from $280 to $335 (Beckmann, n.d.). The area results from the tubes' diameter and the track's length on piers. The maximum price is $1.206 billion and the minimum is $269.5 million.

The cost of the propulsion system depends on the technology used. In the scenario, it was defined that the motors are linear electric motors. But even among linear electric motors, there are still different variants, as described in the foundations chapter. Different costs were therefore estimated for the propulsion costs per kilometer in past research. For example, Delft Hyperloop, at $27.23 million, estimated the cost using maglev systems. However, it has been criticized that the price is much too high because of the guidance used in maglev systems (Kalrav, 2019). Other estimates are much lower, such as that of Transpod, with costs of $0.55 million per kilometer, corresponding to the estimated costs of current research or Hardt Hyperloops estimation of $7.6 million per kilometer.
The cost of magnetic levitation is more challenging to estimate because it depends on the levitation type. Is it active or passive levitation. Together with the cost of the propulsion and control system, AECOM estimates the cost at $2.83 billion for the 500 kilometer double track (AECOM, 2020). Calculated per kilometer, this results in a cost of $2.83 million for propulsion, levitation, and control system. The results are the average of the costs of different types of propulsion and levitation and are therefore used for this report. Thus, the costs range from $3.113 to $3.396 billion.

### 5.1.3 Capsules Costs

The cost of the capsules is highly dependent on the number of passengers. The price consists of the cost of the capsule itself with the seats for the passengers, the entertainment system and the batteries, which are on board to guarantee the power supply. In addition, there are again costs for the propulsion system and magnetic levitation, as these components are present both in the vehicle and on the track. Finally, there are the costs of the control and communication system. Unlike the stations and the track, the costs of the vehicles must be multiplied by the number of vehicles.

There is not enough information to estimate the individual costs, so the costs are determined as a whole for the capsules, including all components. Elon Musk estimated this at a capacity of 28 passengers at $1.75 million per capsule (Musk, 2013). Hardt came to a price of $3.84 million per capsule with 60 passengers (Kalrav, 2019). While another study compares the costs with a Maglev train and comes to a cost of $16.2 to $19.5 million for 90 passengers (van Goeverden et al., 2018). According to AECOM, the cost per capsule for a capacity of 30 to 60 seats is between $2.5 and $7.6 million

(AECOM, 2020). Assuming that the capsules are between $2.8 and $9 million, the cost per seat is around $0.1 and $0.15 million. With the 75 to 100 capsules defined in the scenario, costs range from $210 to $900 million, depending on the capacity of the capsules.

#### 5.1.4 Soft costs and Contingency

Soft costs are expenses necessary to complete the infrastructure project but are not directly used in the construction of the infrastructure. They do not include the construction of bricks and mortar, the purchase of vehicles and equipment, or land acquisition. Instead, soft costs include all expenses incurred by professional services to complete the project (Transportation Research Board et al., 2010). In an Hyperloop infrastructure project, for example, this includes planning, project management, and legal and insurance expenses.
The figures are from AECOM's feasibility study and are adopted as such for this report (AECOM, 2020):

- Preliminary Engineering (3% of subtotal costs)
- Final Design (8%)
- Project Management for Design and Construction (3%)
- Construction Administration and Management (7%)
- Professional Liability and Insurances (2%)
- Legal, Permitting, and Other Fees (1%)
- Surveys, Tests, and Inspections (1%)
- Start-up Costs (1%)

Soft costs therefore add up to 26 percent of the cost of capital. This results in costs of between $7.26 and $16.8 billion.

When planning the costs of a project, so-called contingency costs can be added. This is typically a cost factor set aside for unforeseen costs if they arise during the project. These expenses may result from unpredictable weather conditions, inconsistencies within the project, or imperfect design plans. The factor therefore depends mainly on the detail of the project planning and the level of uncertainty (McMullen, n.d.).
The contingency cost figure is also based on the same feasibility study by AECOM (AECOM, 2020). In this context, 13% of the total costs, which range from $3.62 billion to $8.4 billion, are set as unforeseen costs.

The total cost of capital thus ranges from $38.8 to $89.6 billion, depending on the scenario. The costs per kilometer range from $70.5 to $149.8 million. The capital costs are summarized in Table 1

Table 1 Capital Costs Overview

| Cost center | Minimum cost (Mio. $) | Maximum cost (Mio. $) |
|---|---|---|
| **Station** | Min. | Max. |
| Building | 260.00 | 360.00 |
| Land Acquisition | 252.80 | 336.00 |
| Chambers | 9.68 | 34.00 |
| PV | 8.96 | 13.40 |
| **Total** | **531.44** | **743.40** |
| | | |

| **Track** | Min. (25% Tunnel, 75% Pillar, 550km) | Max. (75% Tunnel, 25% Pillar, 600km) |
|---|---|---|
| Tube | 5500.00 | 9000.00 |
| Pillars | 1650.00 | 1200.00 |
| Tunnel | 9625.00 | 36000.00 |
| Emergency Exit | 1017.50 | 1110.00 |
| Vacuum Pumps | 8.25 | 9.00 |
| ROW | 5445.00 | 11880.00 |
| PV | 808.50 | 402.00 |
| Propulsion / Levitation | 3113.00 | 3396.00 |
| **Total** | **27167.25** | **62997.00** |
| | | |
| **Capsules** | Min. (75) | Max. (100) |
| Capsule | 2.80 | 9.00 |
| **Total** | **210.00** | **900.00** |
| | | |
| **Soft costs 26%** | 7256.26 | 16806.50 |
| **Contingency 13%** | 3628.13 | 8403.25 |
| | | |
| **Total** | **38793.01** | **89850.16** |
| **Total per km** | **70.53** | **149.75** |

## 5.2 Operating Costs

Operating costs, as the name suggests, are all costs associated with the operation of a business. They are the costs that an organization needs to make its existence possible. Operating costs are fundamentally divided into fixed and variable costs. Fixed costs remain fixed, regardless of whether, in the case of the Hyperloop connection, the utilization rate is at 100% or the system is not in operation at all. Variable costs, on the other hand, change with the utilization of the facility (Wikipedia, 2023).

Table 2 Operating Cost Categories and Primary Cost Drivers

| Drivers | | Cost Categories |
|---|---|---|
| **Capsule Kilometers** | → | Equipment Maintenance<br>Energy |
| **Passenger Kilometers** | → | Insurance Liability |
| **Ridership / Revenue** | → | Sales and Marketing |
| **Fixed Cost** | → | Service Administration<br>Track and ROW Maintenance<br>Station Costs |

The operating cost model used later in this paper comes from the railroad industry and was initially developed for the Midwest Regional Rail System and reused in a Feasibility Study for the Rocky Mountain High-Speed Rail System (Transportation Economics & Management Systems, Inc., 2010). Since a hyperloop system can be most closely compared to a railroad. However, minor adjustments were made because operations cannot be covered one-to-one. The Operating Cost Categories and Primary Cost Drivers are summarized in Table 2. The operating cost model developed in the process is mainly consistent with that used in an earlier Hyperloop feasibility study (AECOM, 2020). Fixed costs include service administration, track and ROW maintenance, and station costs. Variable costs include equipment maintenance, energy, crew, insurance liability and sales and marketing. An overview of the operating costs can be seen in Figure 13.

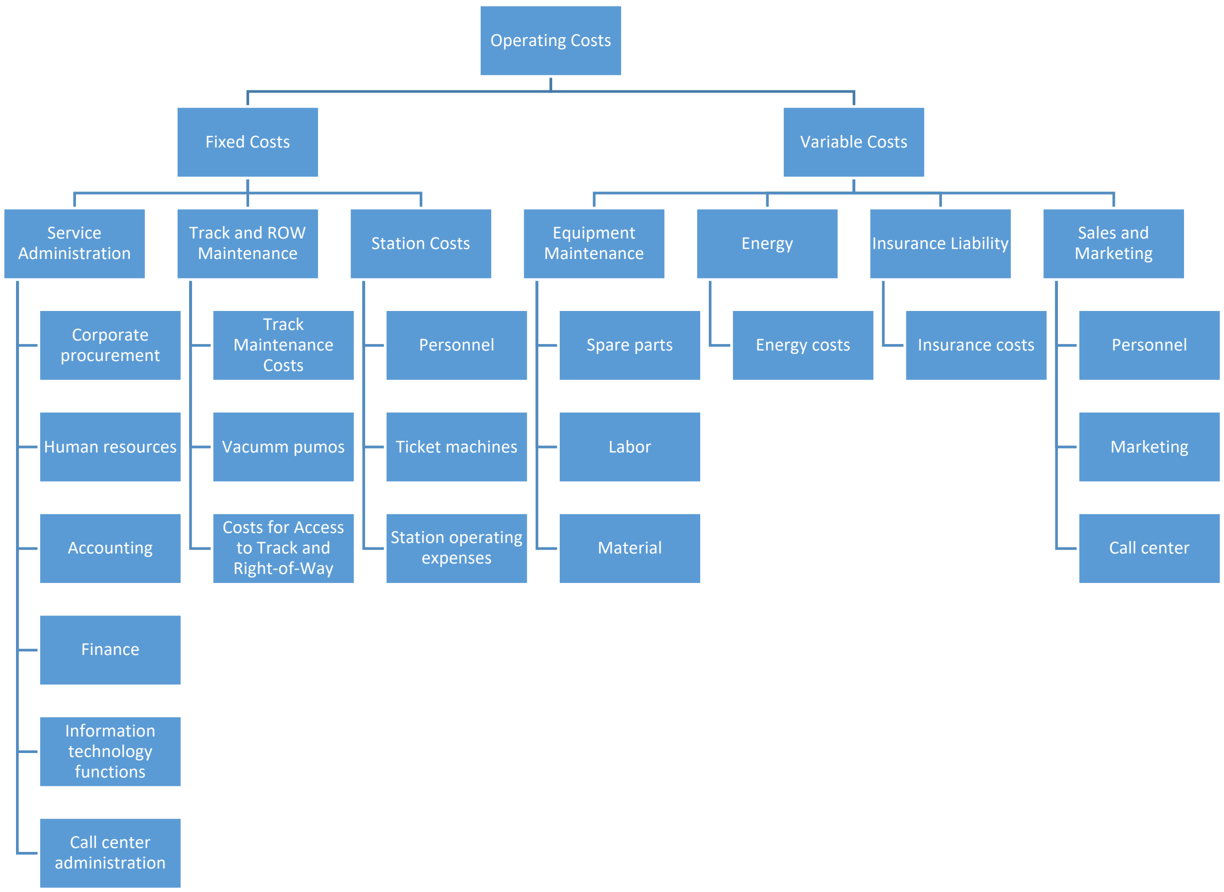


Figure 13 Overview of the operating costs

### 5.2.1 Fixed Costs

Service administration, also known as management overhead costs, describes all costs incurred in connection with corporate procurement, human resources, accounting, finance and information technology functions, as well as call center administration. According to a study in the high-speed rail sector, this cost item generates fixed costs of $15 million per year. Although the cost centers are allocated to the fixed costs, a variable part of approximately $3.95 per km is added (Transportation Economics & Management Systems, Inc., 2010). With a Maglev system, the cost is therefore estimated at about $42 million per year. A comparable study, which among other things, looked at the operating costs of an Hyperloop connection, estimated the system overhead costs at around $73 million (NOACA et al., 2020). This also includes the costs for sales and marketing. Based on these two figures, this report assumes that the annual cost for Service Administration is between $40 and $70 million.

The track and right-of-way costs are made up of these two cost centers. On the one hand, the costs incurred for the maintenance of the track, and on the other hand, the costs for the rights of way. The former includes all costs incurred on the track as well as the costs for energy and maintenance of the vacuum pumps. Conversely, the latter is only incurred if the ground has been leased rather than purchased. Since the scenario is based on a large part of the land purchase, the remaining amount is paid off annually during the leasing period.

A 2020 feasibility study in the field of Hyperloop comes to annual costs of around $160 million (NOACA et al., 2020). The comparative study in the Maglev area calculates yearly costs of about $140 million for the same cost center (Transportation Economics & Management Systems, Inc., 2010). According to another study, the maintenance costs for an Hyperloop system are 10% of the annual capital costs (Kalrav, 2019). Assuming an infrastructure lifetime of 50 years, annual maintenance costs range from around $100 to $200 million, depending on the scenario.

Based on the various estimates, maintenance costs are expected to range from $120 to $180 million annually for track maintenance and rights-of-way.

The costs for the two stations consist on the one hand of the maintenance costs, energy, heating, cooling and so on, and on the other hand of wage costs for the staff. The latter's prices should be kept as low as possible since the focus is mainly on electronic ticketing and Internet booking.

Previous estimates put the cost at around $12 million (NOACA et al., 2020). Other estimates, however, ranged from $16 to $20 million (Transportation Economics & Management Systems, Inc., 2010).

Other reports put station maintenance costs at 10 percent of capital costs. In addition, there are operating costs of $100 per square foot (AECOM, 2020). This would get applied to the scenario cost of $3.7 to 6.7 million.

Due to a lack of data, especially in the area of wages and the number of employees, a range of $4 to $20 in annual station operating costs is assumed.

### 5.2.2 Variable Costs

The cost of spare parts, labor and all material to ensure safe operation falls under the category of equipment maintenance. Not only maintenance work but also regular inspections are taken into account. Thanks to the identical capsules, maintenance can be carried out efficiently and cost-effectively, and warehousing costs can be kept low. Furthermore, standardization is promoted thanks to uniformity, which contributes to a significant cost reduction.

The equipment maintenance cost depends on the number of kilometers traveled by the capsules. A 2020 Hyperloop feasibility study in America puts the cost per kilometer at $0.78 (NOACA et al., 2020). Figures from the rail industry are about ten times higher than those mentioned earlier (Transportation Economics & Management Systems, Inc., 2010). This may make sense since a controlled system like the Hyperloop not only has less friction and thus less wear and tear but is also protected from the environment. Further information again assumes the 10 percent capital cost for maintenance (van Goeverden et al., 2018). When applied to the scenario, this would cost $21 million to $90 million per year. If this is calculated per kilometer, it is conservatively estimated to be around $0.3 per kilometer. Therefore, it is assumed that the annual equipment maintenance cost is between $0.3 and $0.8 per kilometer. This results in a minimum cost of $86.7 million and a maximum of $252.3 million.

The cost of energy, as the name implies, considers the costs that must be spent for the entire system's power. These are dependent on the kilometers driven. Since the infrastructure is equipped with solar panels, part of the required energy can be generated independently.

The energy consumption of an Hyperloop system can be calculated by summing all the components that consume energy and adding the components that add energy. To get an exact number, one has to go into detail, which is difficult. However, EuroTube has come out with a study that says the energy consumption of an Hyperloop system averages out at 0.6 megajoules per kilometer per person

(EuroTube, 2023). This figure is supported by a second study, which states that the energy consumed per kilometer per person is 0.7 megajoules (Hirde et al., 2022). An average kilowatt-hour price of $0.3 Feld (Eidgenössische Elektrizitätskommission, 2022) results in an annual energy cost of $404 million to $1104 million. With the solar panels on the track and those on the stations, it is thus possible to produce 150 to 230 kilowatt hours per year per square meter (iwb, n.d.), which is therefore a total of between 546 million and 671.5 million kilowatt hours. Translating to a price tag of $163.8 million to $201.5 million.

Insurance costs are calculated per passenger kilometer. Since the system operates in a controlled environment, many of the risks can be minimized. For example, all weather-based risks that arise with conventional transportation systems. Therefore, lower insurance costs can be assumed for an Hyperloop system. According to a study of high-speed trains, the insurance cost per passenger kilometer is 0.0075 cents (Transportation Economics & Management Systems, Inc., 2010). According to a second study in the area of Hyperloop, the same expenses are 0.011 cents per passenger kilometer (NOACA et al., 2020). The minimum passenger kilometers traveled in the scenario are 8’094’240’000 kilometers and the maximum 18’921’600’000, resulting in a total annual insurance cost of $60.7 million minimum and $208.1 million maximum.

Sales and marketing can also be considered as system overhead costs, which are listed under fixed costs. However, these costs also have a variable part, which depends on the ridership and revenue. This includes costs such as advertising and call center expenses but also credit card commissions and the like. Putting these cost centers into figures is difficult. To quantify it anyway, consider the Swiss Federal Railways, which spends 1 percent of its revenue on marketing each year (SBB Konzern, 2022). Another study estimates the travel costs for the Hyperloop at $0.2 per kilometer (van Goeverden et al., 2018). This would result in annual revenues of $1.6 to $3.8 billion. This, in turn, results in a marketing budget of $16 to $38 million. Due to a lack of information and data, this is assumed to be an annual sales and marketing cost.

Thus, the total variable cost is between $366.7 to $1438.4 million per year, depending on the scenario. The total operating expenses of an Hyperloop connection from Zurich to Paris amount to between $530.7 and $1708.4 million. An overview can be seen in Table 3.

Table 3 Operating Costs Overview

| Cost Center | Minimum cost (Mio. $) | Maximum cost (Mio. $) | Depending on: |
|---|---|---|---|
| **Fixed Costs** | Min. | Max. | |
| **Service Administration** | 40.00 | 70.00 | Fixed |
| **Track and ROW Maintenance** | 120.00 | 180.00 | Fixed |
| **Station Costs** | 4.00 | 20.00 | Fixed |
| **Total Fixed Costs** | **164.00** | **270.00** | |
| | | | |
| **Variable Costs** | | | |
| **Equipment Maintenance** | 86.70 | 252.30 | Capsule Kilometers |

| | | | |
|---|---|---|---|
| **Energy** | 404.00 | 1104.00 | Capsule / Passenger Kilometers |
| **PV** | -201.50 | -163.80 | |
| **Insurance Liability** | 60.70 | 208.10 | Passenger Kilometers |
| **Sales and Marketing** | 16.00 | 38.00 | Ridership / Revenue |
| **Total Variable Costs** | **366.70** | **1438.40** | |
| | | | |
| **Total Operating Costs** | **530.70** | **1708.40** | |

### 5.3 Interim conclusion

The previous chapter dealt with the cost model of the Hyperloop connection. On the first level, the costs were divided into capital and operating costs. Capital costs are those incurred at the beginning of the construction of the infrastructure. These non-recurring costs were again subdivided into the subcategories stations, track and capsules. Together this results in the total capital costs for the Hyperloop project. In a further step, the operating costs of the Hyperloop connection, using a rail industry cost model, were elaborated. For this purpose, the costs were divided into fixed and variable parts. As the name suggests, the fixed costs are fixed and the variable costs depend on kilometers, passengers or revenue. As a result, the total costs of the Hyperloop connection are available in a range. This is because the costs are subject to a certain degree of uncertainty.

# 6 Simulation

The simulation was performed using basic Excel. Since the calculations are simple correlations executed with basic operations, this is completely sufficient. Two simulations were performed, one for the capital costs and the other for the operating costs. The complete Excel sheets of the simulations can be found in the Appendix. As mentioned earlier, several simulations were run. First, a baseline simulation to determine the expected cost of the Hyperloop connection, followed by a sensitivity analysis to determine the parameters that have the most significant impact on cost. Finally, a Monte Carlo simulation was performed to determine with what certainty the costs can be predicted with the information available.

## 6.1 Baseline Simulation

The baseline simulation shows the expected cost of the Hyperloop connection. For this purpose, a baseline simulation of the capital costs and one of the operating costs was performed. The cheapest option was selected as the baseline for this report. This means all parameters influencing the resulting capital and operating costs were set to create the most economical option. However, this also includes the fact that the solar plants are allocated less area and thus, the electricity costs become more expensive. In other words, for the baseline, the minimum values were taken into account, which does not necessarily always collide with the lowest costs. In essence, the line was set at the minimum of 550 kilometers with a distribution of 25 percent tunnel and 75 percent above ground on support pillars. These pillars have a maximum distance of 30 meters and the tubes running on them have a minimum diameter of 3.5 meters. The capsules floating in them have a capacity for 28 passengers and a total of 75 such capsules are needed. It is assumed that about 50 percent of the land for the line will have to be acquired. For the related costs of the respective components, the lower end of the cost range determined in the previous chapter was always chosen. Based on these assumptions, the baseline simulation was performed for capital and operating costs.

## 6.2 Sensitivity Analysis

In the sensitivity analysis, parameters are determined that have a major influence on the costs of the Hyperloop connection. This serves to either invest more research in these areas in the future to reduce costs or, if possible, bypass these cost centers with alternative variants. The sensitivity analysis was also performed on the baseline scenario, as described above. In each case, a value of the so-called factor levels was increased or decreased to see what effect this change would have on the total costs. The same factor levels were chosen for the capital and operating costs. Essentially, these are the 550-kilometer and 600-kilometer distances and the 25 percent to 75 percent, 50 percent to 50 percent, and 75 percent to 25 percent ratios of the tunnel to support pillars. For the land area, which must be purchased, a distinction was made between 50 percent in the baseline and 100 percent. The number of passengers in each capsule was increased from 28 to 60, and associated with this, the departure times. From every two minutes for 24 hours a day to departures every 5 minutes during only 18 hours a day. This results in the total number of trips from 1440 to 432 in one day. 3.5 meters and 4 meters were taken into account for the diameter of the tube and the distance between the piers from 30 to 25 meters. With these factor levels described, the sensitivity analysis was performed for the two costs based on the baseline.

## 6.3 Monte Carlo Simulation

The Monte Carlo simulation is intended to record the confidence with which costs can be predicted with the available information. The simulation, also known as multiple probability simulation, is a mathematical method that estimates possible outcomes of uncertain events (IBM, n.d.). It was initially developed to improve decision-making under uncertain conditions and is named after the famous district of Monaco, with its many casinos. Similar to casinos, randomness is the basis of the modeling approach. Monte Carlo simulation estimates results based on a range of values instead of a fixed value. Within this range of values, a random number is chosen for the simulation and it can be repeated thousands of times. The result is a probability distribution of the possible outcomes. Since a large part of the definitions and costs in the field of hyperloop are not clearly determined and lie within a minimum and maximum value, a Monte Carlo simulation is ideally suited. This was also performed for the capital costs and the operating costs. The ranges of values were taken from those in the previous chapters and the simulation randomly selects a number in that range. This can be implemented relatively easily in Excel with the existing "Random Number" function. The Monte Carlo simulation was run 1000 times each.

## 6.4 Interim conclusion

The past chapter briefly describes the simulations performed for this report, providing the basis for the following results and discussion. The simulation environment was described in more detail, as well as the individual simulations of the baseline, the sensitivity analysis and the Monte Carlo simulation. This is to ensure the understanding and comprehensibility of the simulations and to provide the basis for subsequent outcomes.

# 7 Results

The results of this report are presented below. In more detail, it is about the overview of the different results of the simulations. Only the results of the definitions mentioned above and cost ranges are presented. The interpretation of these data will be discussed in the following chapter. The results are structured according to the simulations described above.

## 7.1 Baseline Simulation

The baseline simulation of the cost of capital resulted in a total of $38.8 billion. This consists of 70 percent of the cost of the track. The track includes all costs associated with tubes, pillars, tunnels, emergency exits, vacuum pumps, right-of-way, solar arrays, as well as propulsion and levitation. The tunnels alone account for about half of the total costs for the track. Only 1 percent each of the total capital costs are taken up by the station and capsule costs. Although station costs exceed 500 million, they appear negligible compared to the total cost. Soft costs and contingency account for the remaining 30 percent. The baseline simulation can be seen in Figure 14.

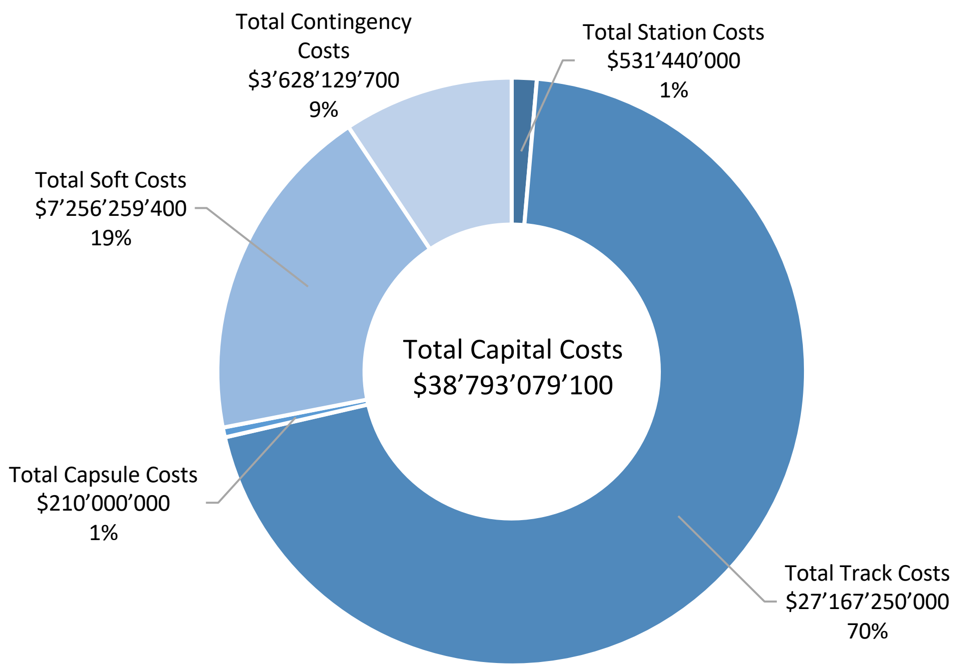


Figure 14 Baseline Simulation of the Capital Costs

The baseline simulation of operating costs came out with a cost of about 530 million per year. These were made up of the above-mentioned fixed and variable costs. The fixed costs remain the same if the line is more or less utilized. Only the variable costs increase or decrease. At 38 percent, energy costs are the most significant contributor to operating costs. These energy costs already include the amount of solar power produced by the system itself. The next largest cost item are the maintenance costs. With around 23 percent, respectively 16 percent for the maintenance of the track, the right of way, and the complete equipment, this results in a little more than one-third of the total costs. The remaining third of the costs comprises insurance costs, service administration, sales and marketing, and station costs. From the point of view of fixed and variable costs, total operating costs are composed of about one-third of fixed costs and two-thirds of variable costs. The total operating costs for the baseline can be seen in Figure 15.

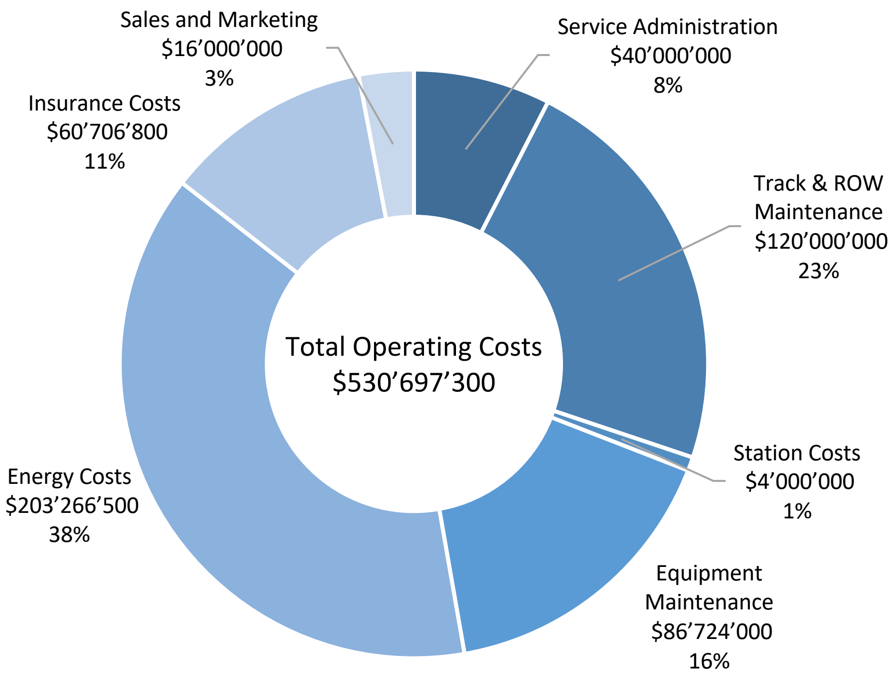


Figure 15 Baseline Simulation of the Operating Costs

## 7.2 Sensitivity Analysis

In the sensitivity analysis, one sees the influence on the total costs when a single parameter is changed. The cost of the tunnels stands out in the sensitivity analysis for capital costs. With the baseline of 75 percent support piers and 25 percent tunnels, there is a cost of $38 billion, as seen earlier. When changed to 50 percent each, the cost already rises to more than $50 billion and eventually to more than $63 billion at 75 percent tunnels and 25 percent support piers. Less surprisingly, costs also increase when more must be spent on land acquisition. Increasing the diameter of the tube from 3.5 to 4 meters and the distance from 550 to 600 kilometers will similarly impact costs. Interestingly, the total costs for the longer distance are logically higher, but the costs per kilometer decrease minimally. Little to no influence has the number of passengers per capsule, the number of trips, and the smaller distance between the support pillars. The sensitivity analysis can be seen in Figure 16.

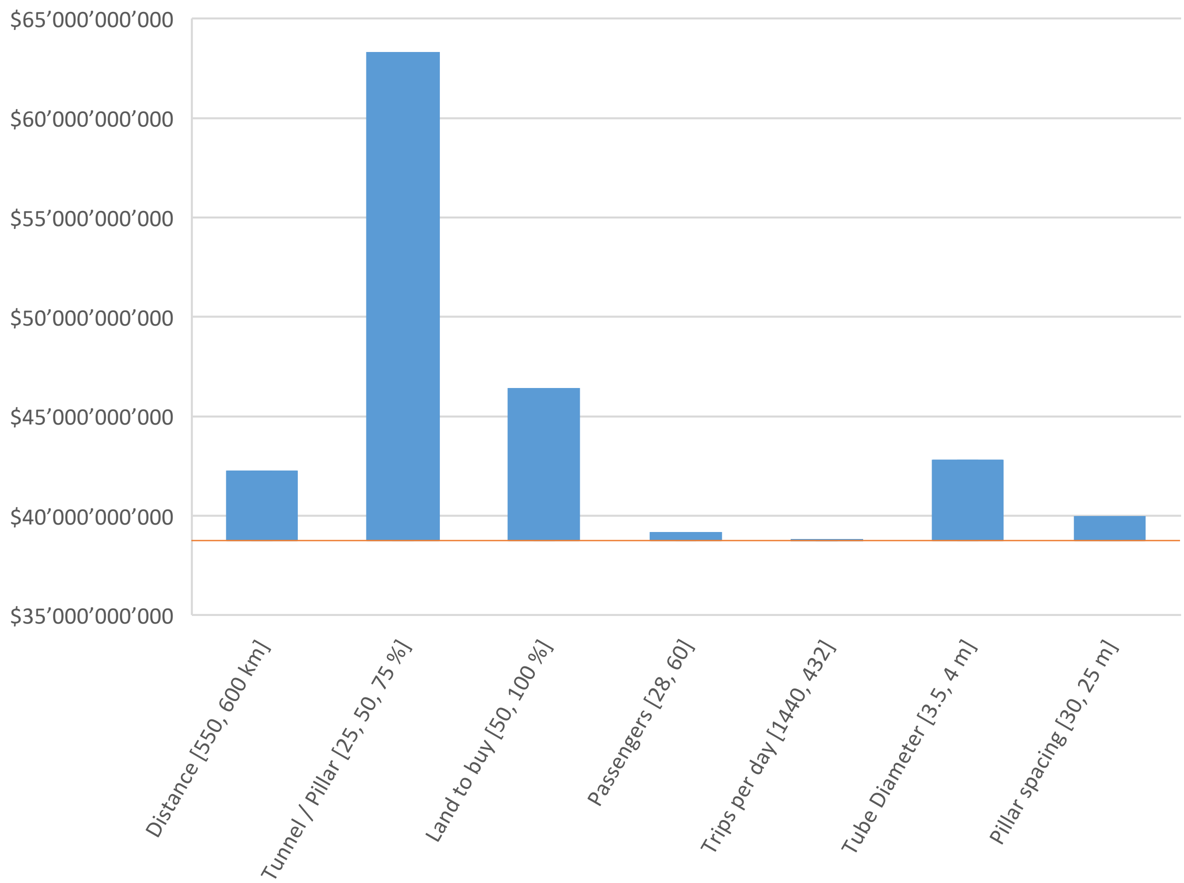


Figure 16 Sensitivity Analysis of the Capital Costs

In the same sensitivity analysis for operating costs, the greatest sensitivity results in the number of passengers per capsule. Both are calculated with full occupancy of the capsules. Annual operating costs roughly double with an increase from 28 to 60 passengers. This is not entirely surprising since the costs of energy and insurance depend on the number of passengers transported. As seen earlier, these two cost centers account for about 50 percent of the operating expenses. With the tunnel-to-pillar ratio, costs increase with more tunnels. Mainly because higher energy costs result since less own electricity can be produced. With a longer track, there are also more maintenance costs. The distance between the pillars and the amount of land that has to be acquired have no influence on operating costs. However, it can be argued that more piers lead to more maintenance costs and less land that was initially acquired leads to more annual right-of-way costs. However, these were not considered due to too little data in the model. A significant cost reduction is achieved when trips are reduced. This is due to a decrease in energy, maintenance, and insurance costs. Also, a decline, although smaller, is achieved by the larger diameter of the tube since more solar power can be generated and thus, less energy costs are consumed. The sensitivity analysis of the operating costs can be seen in Figure 17.

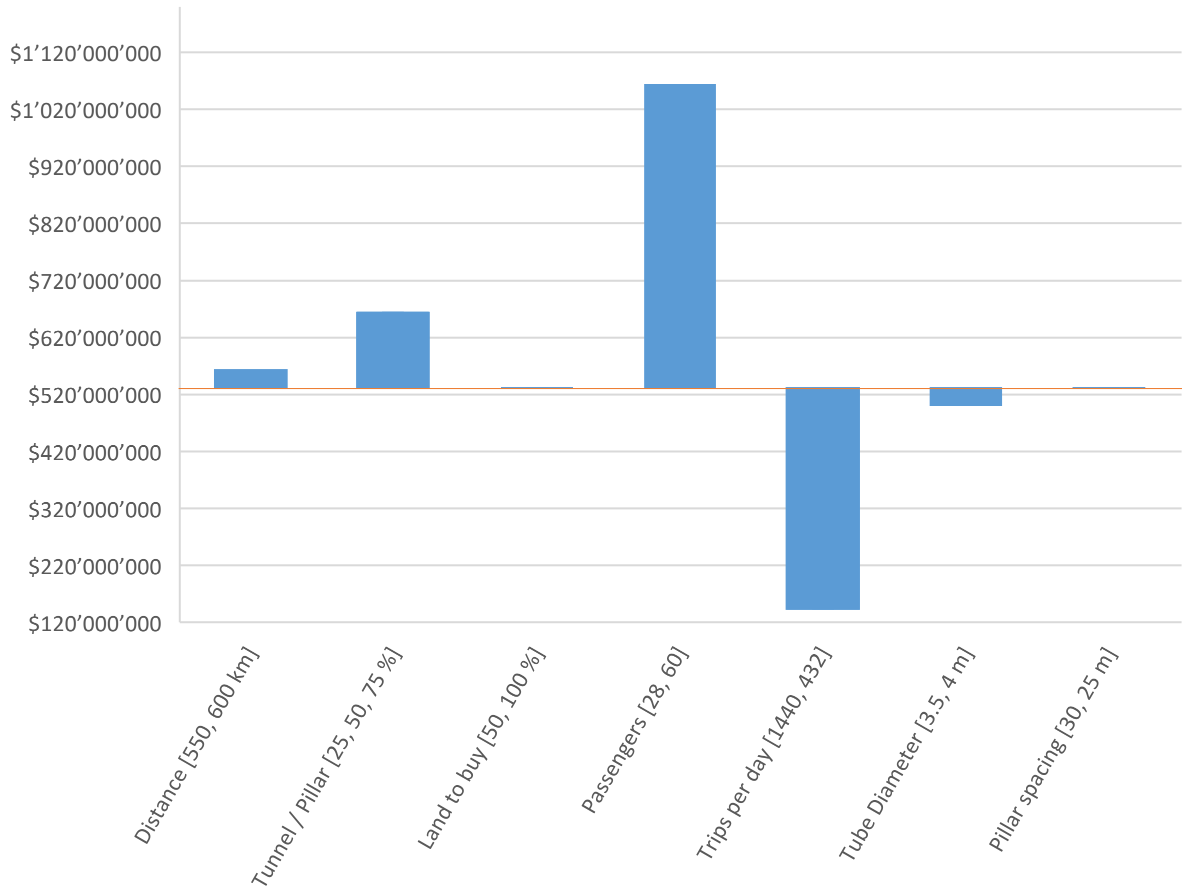


Figure 17 Sensitivity Analysis of the Operating Costs

## 7.3 Monte Carlo Simulation

The probability distribution of the Monte Carlo simulation for the cost of capital over 1000 simulations can be seen in Figure 19. The corresponding boxplot can be seen in Figure 18. The distribution resembles a normal distribution, with the median value at around $62 billion. The 95% probability interval is between $48 and $78 billion. Above and below that, it has outliers from $42 to $84 billion.

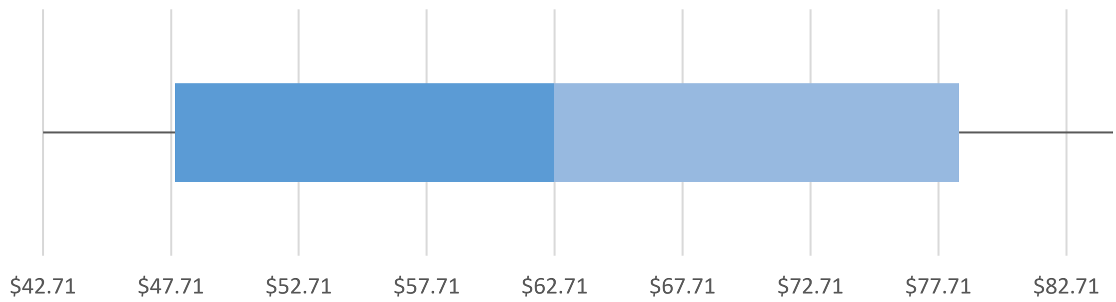


Figure 18 Boxplot of the Monte Carlo Simulation for the Capital Costs

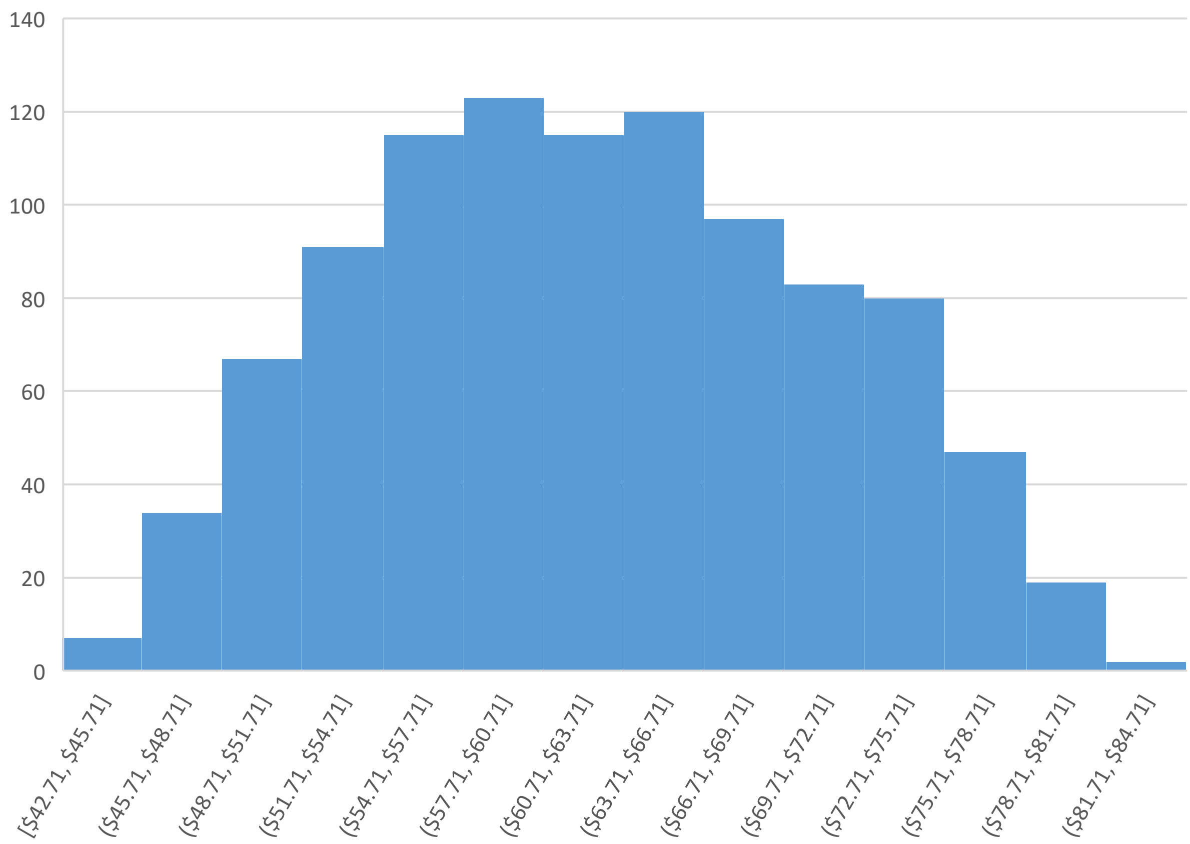


Figure 19 The probability distribution of the Monte Carlo Simulation for the Capital Costs

For the operating costs, a similar distribution can be identified as for the capital costs. On the boxplot of the Monte Carlo simulation for the operating costs, the median value of about $1.13 billion can be identified. With a probability of 95 percent, the values for the annual operation of the Hyperloop connection are between about $800 million and $1.47 billion. The outliers range from $660 million to $1.55 billion. The corresponding figure can be seen in Figure 20. The probability distribution of the Monte Carlo simulation for the operating costs resembles an elongated normal distribution shown in Figure 21.

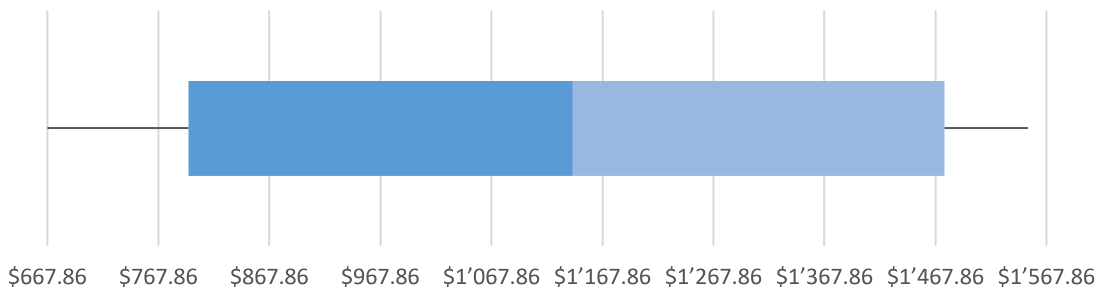


Figure 20 Boxplot of the Monte Carlo Simulation for the Operating Costs

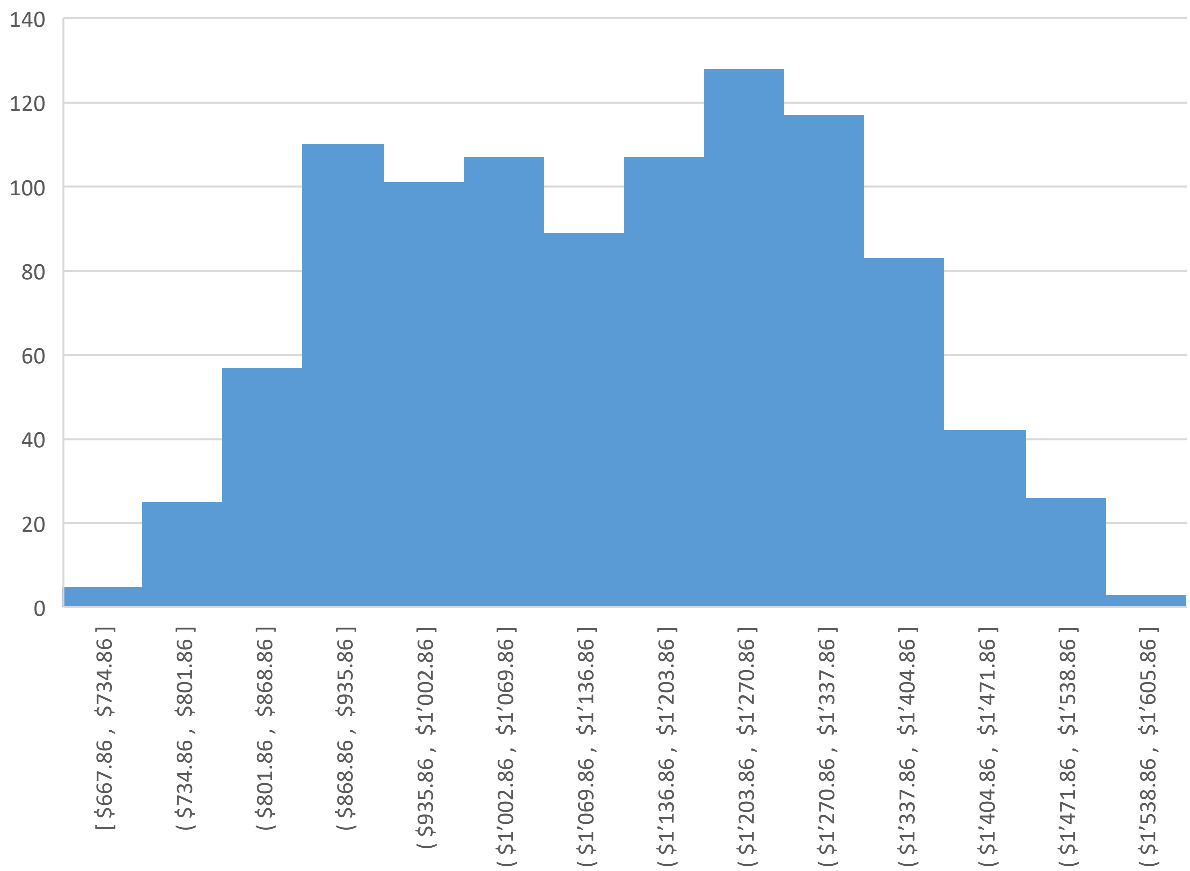


Figure 21 The probability distribution of the Monte Carlo Simulation for the Operating Costs

### 7.4 Interim conclusion

The previous chapter dealt with the presentation of the results for the different simulations regarding the cost of the Hyperloop connection. In the first step, the results of the baseline simulation were shown, which represents the most cost-effective variant of the Hyperloop connection. The results for the capital costs and the operating costs were displayed. From the baseline simulation, the next step was to perform the sensitivity analysis for the two types of expenses. The results obtained for each of the modified scenarios were presented. In the last step, the results of the Monte Carlo simulation were disclosed both for the capital and operating costs.

## 8 Discussion

The aim of this project is to model the operating costs of an Hyperloop connection from Zurich to Paris. Based on the developed scenario in the baseline simulation, it was found that the costs of this connection have an initial capital cost of about $38 billion. The associated sensitivity analysis has shown that the tunnel costs have the most significant impact on the total cost. The effects of land to be purchased, the length of the line and the tube diameter are still substantial but of secondary order. In addition, annual operating costs of around $530 million are estimated to be incurred over the lifetime of the infrastructure. A major influence on these costs is the number of passengers transported per year and kilometers traveled. The length of the line, the proportion of tunnels and the tube diameter have a lesser influence but nevertheless are not negligible. If one considers not only the baseline case but all possible scenarios, as in the Monte Carlo simulation, one must expect a median value of the capital costs of $62 billion and a normal distribution of the costs with a 95 percent probability that the cost will be between $48 and $78 billion. For the operating costs, the median value is $1.13 billion. From the results, a normal distribution can also be identified with a 95 percent probability that the cost will be between $800 million and $1.47 billion. In the following, these results are now interpreted and analyzed to answer better the question of what the expected costs of an Hyperloop connection are.

### 8.1 Capital Costs

The baseline simulation provides information about the costs of an Hyperloop connection from Zurich to Paris based on the developed scenario. The expected cost of capital is approximately $38 billion. If this is calculated per kilometer, the price per kilometer is about $70 million. This is somewhat higher than previous estimates but still within the reasonable range. Figure 22 shows previous cost estimates. The reasons for the higher costs are the more expensive tunnel and the consideration of land acquisition. Since tunnels happen to be more costly than variants on pillars, costs can be reduced by eliminating tunnels. Looking at the baseline scenario without tunnels but with pillars, the cost per mile is about $48 million, similar to the previous estimates. Thus, in the cheapest comparison by Elon Musk and the most expensive one by AECOM, both have no tunnels in the route. AECOM's study completely omits the cost of land acquisition. Elon Musk assumes that a large part will be built along existing highways and therefore little land will have to be acquired. In his estimate, the land acquisition is put at a flat rate of $1 billion. In this baseline simulation, it is about $6 billion. As a consequence, capital costs increase when the more expensive tunnels are used and land acquisition costs are added.

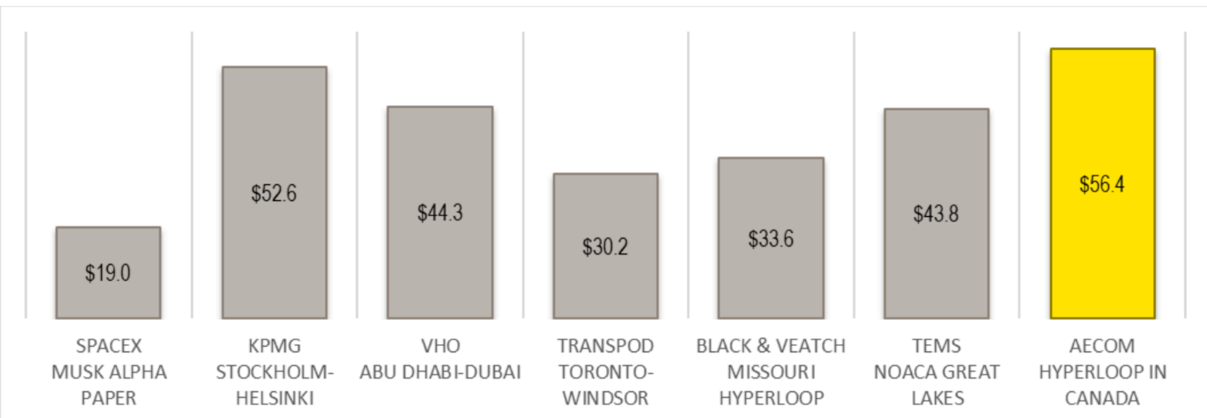


Figure 22 Capital Cost Estimates from Previous Hyperloop Studies (2020 $ M) (AECOM, 2020)

As can be seen from the results, the most significant part of the cost is the construction of the line. This is not entirely surprising since it represents a large part of the infrastructure and the subcategories are quite expensive. In contrast, the costs for the capsules and the stations are negligible. In addition, there are only the soft costs and the costs for contingencies.
Previous cost estimates also confirm the fact that the track represents a significant cost factor. In Elon Musk's Hyperloop Alpha, the track accounts for around 90 percent of the costs, while in AECOM's study, it accounts for about 66 percent. The capsules and the stations are also comparatively small in both cases. Therefore, it will be possible to have the greatest impact with the route's cost. The reduction of the costs of the stations or the capsules brings only a small reduction of the total costs. On the other hand, if the costs for the line are reduced, a large part of the costs can be saved. This insight is important in the field of future research.

In the sensitivity analysis, the significant cost increase with a higher tunnel share immediately stands out. This was expected since the cost of one kilometer of tunnel is about 17.5 times more expensive than the same route on supporting pillars. This results accordingly in an enormous increase in costs when using more tunnels. The reason for this, simply put, is that the cost of building a tunnel is more complicated than simply building support on the ground and installing the tube on top of it. Therefore, on the one hand, route planning is of great importance in terms of infrastructure planning and, on the other hand, there is great potential to make this technology more affordable. Elon Musk has started a new competition with his Boring Company after he abolished the Hyperloop competition. In this, he encourages research and student teams to build a tunnel-boring machine. Currently, the idea is to build cheap tunnels for car traffic in cities to relieve traffic and get the cities free of cars. But in the long run, the so-called not-a-boring competition will make the Hyperloop possible.

That the costs for the infrastructure for a more prolonged route increase is anything but surprising. The reason for this is that more must be built, which increases not only the cost of materials but also the cost of construction. What is interesting, however, is the cost per kilometer, which decreases slightly for a longer route, as seen in Figure 23. This can be relevant when deciding whether to go around a mountain or build a tunnel. Bypassing the route not only has the advantage of saving the cost of the tunnel but also lowers the price per kilometer for the thereby longer route. The only thing to consider is the large curve radius, which must be taken into account at high speeds.

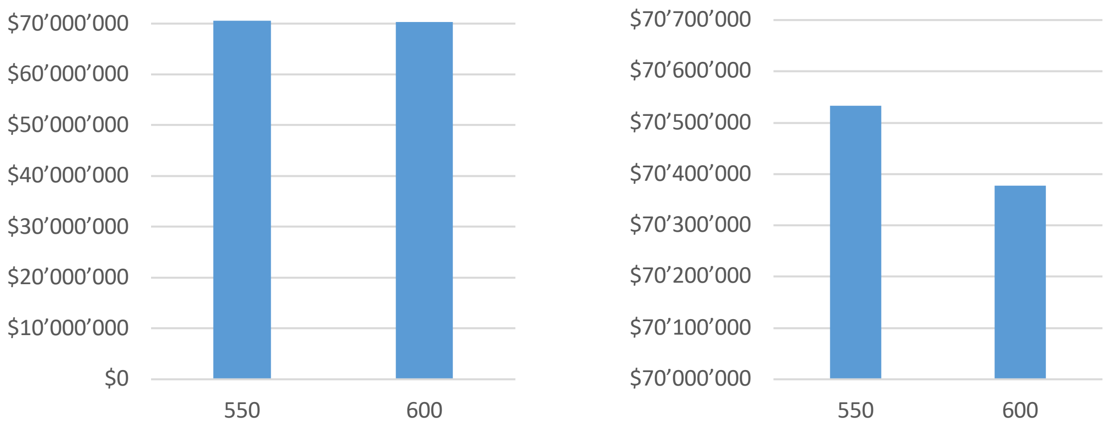


Figure 23 Costs per Kilometer decrease with a longer line

The cost of land acquisition also increases, of course, the more land that needs to be purchased. This is nothing surprising and was expected. For the purpose of land acquisition, a part of the land can be bought and a part can be obtained through the right of way. In the case of a right of way, a private plot of land can be used for roads or railroads, for example, in return for an annual usage fee paid to the owner. To better predict the costs for this area, a more detailed route planning is needed, as well as more precise information on the land costs and rights of way of the countries concerned. Elon Musk had an interesting solution for this problem. As already mentioned, he planned the route along existing highways in order to acquire no or as little land as possible. In addition, he argues that the support pillars only take up a minimal area of land and therefore, only the ground around the pillar must be acquired. In further investigation, it would have to be clarified whether it is sufficient to buy only small parts of the land or whether the entire surface must be acquired. The same applies to land that already belongs to the state. The question is how far this land must be purchased or whether this is made available since it is a construction for the general public.

A larger diameter of the tubes also corresponds to a higher price and the tube will be more expensive because of more material. But on the other hand, the infrastructure around the tube will also be more expensive because it has to be adapted for the larger tube and the associated heavier weight. Standards are essential to establish a compatible Hyperloop network across the board. Currently, there are no such standards, but work is in progress. So it certainly makes sense to standardize a uniform diameter to guarantee the compatibility of the lines. Once such a standard is established, the costs can also be better estimated. Another question is which material will prevail. In the scenario, steel was used, but EuroTube presented a concrete tube that is dense enough to create a vacuum. The advantage of such a concrete tube is the lower cost of manufacturing and production directly on the construction site. The disadvantage, however, is the increased energy consumption for the vacuum, as the tubes are not as tight as steel tubes. It would therefore be interesting to analyze whether the more expensive steel tubes, coupled with the lower energy consumption, are more worthwhile in the long term than the cheaper concrete tubes in connection with the higher energy costs for vacuum maintenance.

The Monte Carlo simulation shows to what certainty the costs can be predicted with the information available. The infrastructure costs of about $38 billion were not hit once in the Monte Carlo simulation. This is unsurprising since every parameter would have to be randomly set to the minimum value. The median is $62 billion and thus more than 1.5 times the costs of the baseline simulation. With this expense, the cost per kilometer also rises to $100 million. Compared to the above studies, this is a doubling, if not more. The reasons for this remain the same. One is the more expensive route for the tunnel, which is higher on average in the Monte Carlo simulation. On the other hand, the costs for land acquisition were not considered in the comparative studies. The probability is 95 percent that the infrastructure cost is between $48 and $78 billion. The consequences of this are that route planning is becoming even more critical. This is because it can save a tremendous amount of costs. Furthermore, with expensive infrastructure costs, expensive travel costs for passengers are also expected, which could reduce the attractiveness of the Hyperloop. This situation will also be less attractive for potential investors, who must dig deeper into their pockets. A clever and well-thought-out route planning can reduce the costs of an Hyperloop system enormously and thus make the technology more interesting for investors and the benefit possible for future passengers.

## 8.2 Operating Costs

Annual costs of about $530 million are expected under the baseline scenario. The operating costs are somewhat more challenging to compare with existing estimates, as few are available. One of the few comparative studies of Hyperloop operating costs predicts a cost of $436.53 million, as can be seen Figure 24. For comparison, Figure 25 shows the operating costs of this report. The study uses the same cost model from the rail industry. Converting the 2018 dollars used in the study to 2023 dollars yields $528 million, about the same as the results in this report. However, this should be taken with a grain of salt, especially since the two scenarios differ. Accordingly, the composition of the costs also varies.

Regarding operating costs, the largest share of costs is allocated to energy costs. At 38 percent, this represents a significant portion of the overall expenses. According to a study by TEMS (NOACA et al., 2020), energy costs are only about 6 percent of annual costs. According to another study (ARUP et al., 2017), they are around 18 percent. In this report, the energy cost depends on the kilometers traveled and the number of passengers transported. In the baseline scenario, the line is assumed to operate at 100 percent capacity and 24 hours a day, so the cost of energy is high. If the occupancy rate is lower or the line operates less regularly, the energy cost decreases significantly and can even become negative with the generated solar energy.

Closely related to this are also the costs of insurance and equipment maintenance. These also depend on the number of kilometers traveled or the number of people transported. If one assumes a less utilized system, the costs in these areas also decrease strongly.

Only the fixed costs are immune to this. These are relatively manageable, with a share of about one-third in the baseline.

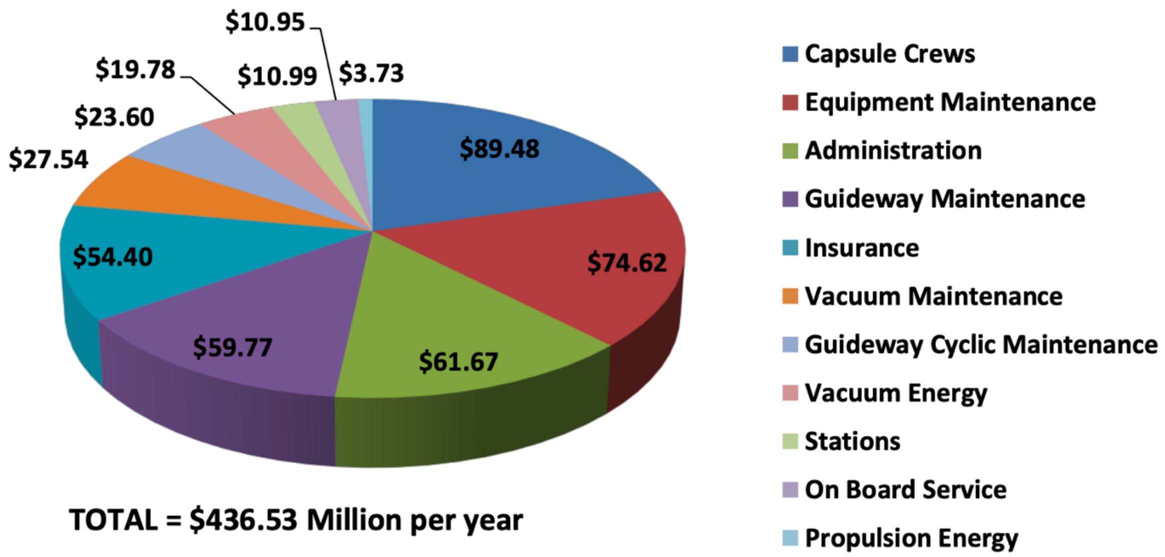


Figure 24 Hyperloop operating costs of a comparative study (2018 $ M) (NOACA et al., 2020)

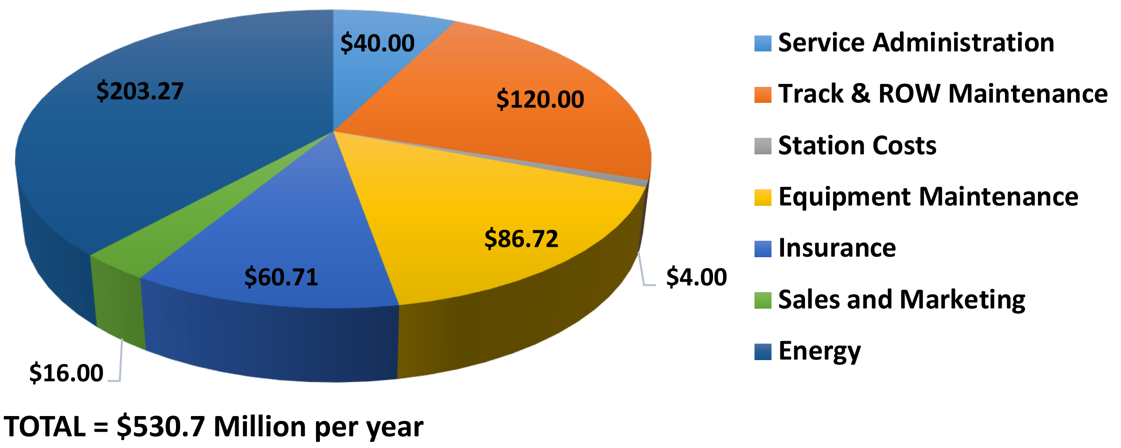


Figure 25 Hyperloop operating costs of this study

The impact of each cost center on annual operating costs is opposite to infrastructure costs. As mentioned, operating costs strongly depend on the kilometers driven and the passengers transported. This is again confirmed in the sensitivity analysis. With more passengers, the annual costs increase strongly. This is, on the one hand, related to the insurance costs, which are calculated per passenger, and on the other hand, due to the energy costs, which also have a variable person-based component. The modeled costs are based on the assumption that the system is at all times fully loaded and in maximum operating condition. Therefore, the costs in these areas are expected to be high and have a corresponding impact.

However, to estimate the costs more accurately, a detailed study of the use of an Hyperloop connection is required. Therefore, if it can be determined how many people use the service, the costs can be predicted more reliably.

This is closely related to the number of trips. These are also variable and have an enormous influence on the operating costs. As seen in the sensitivity analysis, operating costs decrease sharply the fewer trips are made per day. This is expected, as the variable costs for equipment maintenance and the energy consumed decrease with fewer kilometers driven. So if it can be predicted how many passengers will use the connection in a year and how many journeys are necessary to meet the demand, more precise information can be given about the operating costs.

The cost increase resulting from the longer distance comes from the maintenance costs, calculated per kilometer and the energy costs. A part can be compensated by the higher production of the solar plants of the resulting larger surface. This is also why the costs increase with a higher tunnel share: Less solar energy can be produced, resulting in higher electricity costs. However, the cost impact becomes smaller when the line is less utilized. Thus, the variable costs even go into negative territory if the number of daily trips is reduced to 432. This means an operation time of 18 hours and departures every 5 minutes. The variable costs then become negative because the solar plants generate more and thus compensate for the remaining costs. Therefore, with this variant, additional solar arrays can also be omitted to still generate enough electricity. This, in turn, compensates for the annual cost increase with a higher tunnel ratio. As a consequence, annual costs can be saved if the route is shorter. However, a shorter route would again mean that more tunnels would likely have to be built. This is because obstacles do not have to be bypassed. With more tunnels, the operating costs increase again and this is with a larger factor than the longer distance. Thus it can be said that also in terms of operating costs, it is again worthwhile to build a longer route on supporting pillars than a shorter route that runs more directly and increasingly through tunnels.

Similar things can be said about the Monte Carlo simulation of operating costs as for capital costs. The baseline costs were not hit in any of the 1000 simulations since all parameters had to be randomly set to the minimum, this is anything but surprising. The median value is $1.13 billion, more than double the baseline estimate and the comparison study. Again, the reason for this is the high rate of trips per year and the assumed 100 percent utilization of the capsules. Further, the Monte Carlo simulation indicates a 95 percent probability that the operating costs will be between $800 million and $1.47 billion. Finally, it can be said that with a well-planned routing, not only capital costs can be saved, but also annual operating costs. However, most of these costs are still attributable to the passengers transported and the kilometers traveled. Therefore, there is no way around a more accurate estimate of operating costs without a better understanding of the utilization of the connection. As soon as it can be determined precisely how many people per year use the Hyperloop connection and how many journeys are necessary, the operating costs can be predicted more accurately.

## 8.3 Limitations and Restrictions

The scenario itself already represents a major uncertainty factor. Currently, various Hyperloop technologies are under discussion and which one will ultimately prevail is not clear at this point in time. Of course, different technologies also mean different costs. Suppose the levitation of the capsules in the tubes is realized using air bearings, as in Elon Musk's original paper or as the company Zeleros currently has in mind. In that case, different costs arise compared to when it is realized by means of magnetic levitation, as most other companies in the Hyperloop field. The costs of an Hyperloop connection can be predicted more precisely, the more detailed the technologies are known and the more precisely a scenario can be defined. The scenario developed in this report therefore serves as an approximation of this, but at this point, no definitive details of a future Hyperloop connection can be made. Therefore, most of the definitions are merely assumptions and cannot be fully validated.
The cost model was taken from the rail industry and adapted to the Hyperloop concept. Because of the similarity between a railroad and an Hyperloop, this can be considered reasonable. But again, only assumptions are made. The cost model represents the most important and influential cost centers. However, depending on changes in the scenario or the technologies used, the cost model for an Hyperloop may change or be completely adopted.
The costs of the individual cost centers within the cost model are also subject to uncertainties. In the report, these uncertainties were taken into account by working with ranges for the input parameters. Costs can be estimated more reliably for known technologies, but this is difficult for novel or Hyperloop-specific ones because no commercial Hyperloop connection has ever been built. For example, these technologies are still in their infancy or have never been realized. Therefore, the costs used in this report should be used with caution. Nevertheless, they provide valuable estimates and, more importantly, insight into missing or half-true knowledge that should be obtained in the future.
Hence, the goal of this report is not to model the costs of a hypothetical Hyperloop connection as closely as possible but to strengthen the general knowledge about the costs of the Hyperloop concept. The scenario developed, the cost model used or the parameters found may or may not be accurate in the end. But the value comes from the analysis and interpretation of the simulations and what they say about the future of the Hyperloop regarding the costs.

## 8.4 Future of Hyperloop

In order to integrate Hyperloop systems into the transportation infrastructure in the long term, they must be financially viable in addition to the general advantages of existing transportation systems. Of course, this depends on the infrastructure costs on the one hand and the annual operating costs on the other. This will have an impact on the costs for passengers. Obviously, they want a service that is as cheap as possible or at least more affordable than the other alternatives. An incentive is also the faster travel time. However, higher costs definitely have an effect on higher ticket prices.
Before even building a commercial connection, the most critical standards should be set before there will be complications afterward. It is also important to consider the lifetime of the infrastructure. This should become operational for as long as possible so the costs can be amortized over the years. The same applies to the technologies used. These should be mature, remain functional for a long time and, if possible, not be replaced by new technologies. So it makes perfect sense to concentrate on developing the Hyperloop technology, as it is already being done at the moment.
For the infrastructure costs, the most important thing is the planning of the route. With sensible planning, many costs can be saved. Including, of course, the costs for tunnels but also for land acquisition. Tunnels can also have advantages, for example, the existing landscape is not obstructed and there is more space for other buildings. Therefore, it makes sense to be able to reduce the costs of tunnels. This is already being done with the mentioned challenge of Elon Musk Boring Company. In addition, route planning is also a social and political issue. At the beginning of the construction of the Gotthard tunnel, five different route plans were discussed (Schweizerische Eidgenossenschaft, 1988). In the end, a political decision was made in favor of one variant. Even an Hyperloop route is not immune to such hurdles. Apart from political and social issues, individual objections and environmental protection objections also stand in the way of free route planning. To better understand the operating costs, it is necessary to have comprehensive knowledge about the passenger volume of the Hyperloop connection. Once an understanding of how many people use the service is gained, many other parameters emerge. For example, the number of seats in a capsule, how often these capsules have to travel, how many capsules are needed, or how many kilometers are traveled per year. As seen in the previous chapter, the largest variable cost centers are precisely dependent on this information. That is the number of passengers transported and the number of kilometers covered.

## 8.5 Interim Conclusion

The previous chapter dealt with the analysis and interpretation of the results. The underlying cost model of the simulation was scrutinized. It combines the scenario, the cost model itself and the parameters contained therein. Subsequently, the actual results of the simulation were examined in more detail and discussed, what they now mean and what effects they will have. Finally, the future of the Hyperloop was critically examined and questioned, taking into account the results. In conclusion, the work achieves its goal. The costs of the hypothetical Hyperloop connection from Zurich to Paris were sufficiently quantified. In addition to these results, the work highlights a clear direction in which future research must go in order to make the success of the Hyperloop concept a reality.

## 9 Final considerations and outlook

Transportation, both of people and goods, is an essential part of modern civilizations. For a long time, the known means of transport have been established and it seemed that not much would change. However, humans have always strived for continuous improvement and optimization. Consequently, transport and traffic systems are no exception. Getting from A to B faster and cheaper is particularly tempting. Another development has fueled this demand in recent years. Global warming and the associated climate crisis have fueled efforts to establish a sustainable means of transportation. On the road, this is represented by electric cars, hydrogen trucks or e-fuel-powered vehicles. The same approaches are also being tested in the other transport sectors of rail, water and air. But despite the promising prospects of these new technologies, the question of a novel, fifth transport mode arises. One that combines the advantages of the existing ones and fits into the existing landscape. The talk is about the Hyperloop concept, which promises high speeds at a low footprint. And as seen at the beginning of this report, this is indeed a promising alternative, especially since it is still in its infancy. Research is being conducted on the technology worldwide and it is only a matter of time before a breakthrough is achieved and the first commercial connections are put into operation. Until then, however, many unanswered questions remain to be clarified. In addition to the technical, regulatory and safety-related ones, there are also the economic aspects. No serious investor will ever invest money in Hyperloop if he is not fully informed about the costs. But the question of costs is also important in the area of future research. This report took this as a goal and dealt with modeling the costs of an Hyperloop connection. The hope is to advance the technology and pave the way for further research.

### 9.1 Summary of the results

The results of this report are based on the scenario developed previously and the cost model developed. The scenario was derived from the state-of-the-art in the field of Hyperloop via research and comparison of the most important players. The cost model is based on an established one in the rail industry and was adopted because of the similarity and adapted to the requirements of the Hyperloop. A baseline simulation of the costs for the most favorable scenario was performed. Subsequently, a sensitivity analysis would be performed on the baseline. Finally, a Monet Carlo simulation of the total cost ranges was performed.
The baseline cost of capital is $38 billion. Calculated over the kilometer, this is $70 million. At 70 percent, the costs for the track have the most significant impact. Those for stations and capsules are negligible at around 1 percent each. The ratio of supporting pillars to tunnels has the biggest sensitivity to these costs. The more tunnels are built, the more expensive the infrastructure becomes. The right-of-way costs, the tube diameter and the route length follow this. The Monte Carlo simulation's median value is about 1.5 times higher than the baseline at $62 billion. With a 95 percent probability, the cost is between $48 and $78 billion.
The operating costs, which are incurred annually, are $530 million. Most of this is the energy costs that the system consumes. These are highly dependent on the number of passengers and kilometers traveled. These two parameters also represent the greatest sensitivity. Other major cost centers are maintenance and insurance costs. In the Monte Carlo simulation, over 1000 runs, the median value is $1.13 billion annually. This is about twice the baseline simulation. Here, the 95 percent probability of the costs is between $800 million and $1.47 billion. The probability distribution of the two Monte Calo simulations resembles a normal distribution.

## 9.2 Future need for research

Through the results, and rather through the interpretation and analysis of them, new insights into future research emerge. Basically, the general uncertainty in the area of the costs of an Hyperloop system stands out. Due to the unknown system characteristics of the Hyperloop technology, it is difficult to predict a valid cost model. Once the technology is more thoroughly researched and a precise technology combination emerges, further and more accurate cost information can be provided. Therefore, the efforts of the many research groups and companies in the field of Hyperloop technology must be continued and encouraged. After all, these will form the basis of future cost estimates. In this context, and less related to cost, overarching standards and regulators are also essential. The future of the Hyperloop should be one of cooperation and not one of opposition, with everyone looking for themselves, eventually leading to incompatible and competing systems. For this, the research and establishment of the most important definitions is also essential for developing the Hyperloop itself and a more accurate prediction of the costs.

This report shows that the importance of route planning is greatest in the area of capital costs. The cost of the track itself is by far the most expensive cost center. In order to make it cheaper, further research around the line is needed. In particular, the tunnels are a major cost factor. There are two possibilities. Intelligent route planning without tunnels to reduce costs or building tunnels more cheaply. Elon Musk has already recognized this and calls for research into low-cost tunnel-boring machines.

In terms of operating costs, the costs are particularly dependent on the kilometers driven and the people transported. Around two-thirds of the annual costs depend on these factors. To date, no information is known about what an Hyperloop connection would entail for traffic volumes. More research into demand forecasting is needed to better predict operating costs. Knowing the expected volume and utilization of the system will not only provide more accurate information on operating costs but also allow for more accurate planning of the infrastructure in retrospect.

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# Appendix

| Name | Min. | Max. | CurVal. (Min) |
|---|---|---|---|
| operating days | 365 | 365 | 365 |
| operating hours | 24 | 24 | 24 |
| departure frequency | 2 | 2 | 2 |
| cruising speed | 700 | 1000 | 700.00 |
| acceleration G | 0.15 | 0.15 | 0.15 |
| acceleration m/s^2 | 1.47 | 1.47 | 1.47 |
| distance | 550 | 600 | 550.00 |
| tunnel | 25 | 75 | 25.00 |
| pillar | 25 | 75 | 75.00 |
| pillar spacing | 25 | 30 | 30.00 |
| pump frecuency | 10 | 10 | 10 |
| preassure | 100 | 100 | 100 |
| tube diameter | 3.5 | 4 | 3.50 |
| Emergency Exit | 600 | 600 | 600 |
| Siwss | 20 | 20 | 20 |
| France | 80 | 80 | 80 |
| land to buy | 50 | 100 | 50.00 |
| Passengers | 28 | 60 | 28 |
| Regenerative braking | 80 | 90 | 90 |
| Capsule weight | 15 | 26 | 15 |
| Capsules | 75 | 100 | 75 |
| Number of Tubes | 2 | 2 | 2 |
| Track width | 30 | 30 | 30 |

| | | | |
|---|---|---|---|
| Stations | 2 | 2 | 2 |
| Station costs | $130’000’000.00 | $180’000’000.00 | $130’000’000 |
| **2 Station costs** | | | **$260’000’000.00** |
| Square meter price Swiss | 7800 | 7800 | 7800 |
| Square meter price France | 8000 | 9000 | $8’000 |
| Square meter Swiss | 16000 | 20000 | 16000.00 |
| Square meter France | 16000 | 20000 | 16000.00 |
| Land Station Zurich | | | $124’800’000.00 |
| Land Station Paris | | | $128’000’000.00 |
| **Total land Station** | | | **$252’800’000.00** |
| Chamber Zurich | 4840000 | 17000000 | 4840000.00 |
| Chamber Paris | 4840000 | 17000000 | 4840000.00 |
| **Total Chambers** | | | **9680000.00** |
| PV per m^2 | 280 | 335 | 280.00 |
| **Costs PV** | | | **8960000** |
| **Total Station Costs** | | | **$531’440’000.00** |

| | | | |
|---|---|---|---|
| Tube per km | $10’000’000.00 | $15’000’000.00 | $10’000’000.00 |
| **Cost Tube** | | | **$5’500’000’000.00** |
| Pillar per km | $4’000’000.00 | $8’000’000.00 | $4’000’000.00 |
| **Cost Pillar** | | | **$1’650’000’000.00** |
| Tunnel per km | $70’000’000.00 | $80’000’000.00 | $70’000’000.00 |
| **Cost Tunnel** | | | **$9’625’000’000.00** |
| Emergency Exit per km | | 1850000 | $1’850’000.00 |
| **EX Costs** | | | **$1’017’500’000.00** |
| Number of pumps | | | 110 |
| Pump cost | | 75000 | $75’000.00 |
| **Total Pump Cost** | | | **$8’250’000.00** |
| Square meter swiss | | 900 | $900.00 |
| Square meter france | | 600 | $600.00 |
| **ROW** | | | **$5’445’000’000.00** |
| **PV** | | | **$808’500’000.00** |
| Propulsion / Levitation per km | | 2830000 | 2830000 |
| **Propulsion / Levitation costs** | | | **$3’113’000’000.00** |
| **Total Track** | | | **$27’167’250’000.00** |

| | | | |
|---|---|---|---|
| Cpasule per seat | 100000 | 150000 | $100’000.00 |
| Capsule cost | | | $2’800’000.00 |
| **Total Capsule Costs** | | | **$210’000’000.00** |

| | | | |
|---|---|---|---|
| **Total** | | | **$27’908’690’000.00** |

| | | | |
|---|---|---|---|
| Soft costs | 26 | 26 | 26 |
| **Total Soft Costs** | | | $7’256’259’400.00 |

| | | | |
|---|---|---|---|
| Contingemcy | 13 | 13 | 13 |
| **Total contingency** | | | $3’628’129’700.00 |

| | | | |
|---|---|---|---|
| **Total Capital Costs** | | | **$38’793’079’100.00** |
| **Total Capital Costs per km** | | | **$70’532’871.09** |

| Name | Min. | Max. | CurVal. (Min) |
|---|---|---|---|
| operating days | 365 | 365 | 365 |
| operating hours | 24 | 24 | 24 |
| operatin min | | 1440 | 1440 |
| departure frequency | 2 | 2 | 2 |
| cruising speed | 700 | 1000 | 700.00 |
| acceleration G | 0.15 | 0.15 | 0.15 |
| acceleration m/s^2 | 1.47 | 1.47 | 1.47 |
| distance | 550 | 600 | 550.00 |
| tunnel | 25 | 75 | 25.00 |
| pillar | 25 | 75 | 75.00 |
| pillar spacing | 25 | 30 | 30.00 |
| pump frecuency | 10 | 10 | 10 |
| preassure | 100 | 100 | 100 |
| tube diameter | 3.5 | 4 | 3.50 |
| Emergency Exit | 600 | 600 | 600 |
| Siwss | 20 | 20 | 20 |
| France | 80 | 80 | 80 |
| land to buy | 50 | 100 | 50.00 |
| Passengers | 28 | 60 | 28 |
| Regenerative braking | 80 | 90 | 90 |
| Capsule weight | 15 | 26 | 15 |
| Capsules | 75 | 100 | 75 |
| Number of Tubes | 2 | 2 | 2 |
| Track width | 30 | 30 | 30 |

| **Fixed Costs** | | | |
|---|---|---|---|
| Service Administration | 40000000 | 70000000 | 40000000 |
| Track & ROW Maintenance | 120000000 | 180000000 | 120000000 |
| Station Costs | 4000000 | 20000000 | 4000000 |
| **Total Fixed Costs per year** | | | **164'000'000.00 CHF** |

| **Variable Costs** | | | |
|---|---|---|---|
| Equipment Maintenance pe | 0.3 | 0.8 | 0.30 CHF |
| **Equipment Maintenance** | | | **86'724'000.00 CHF** |
| Energy per km per person ii | 0.6 | 0.7 | 0.6 |
| Costs per kWh | | 0.3 | 0.3 |
| km per persone per year | | | 8094240000 |
| MJ per persone per km per year | | | 4856544000 |
| MJ in kWh | | 0.277777778 | 0.277777778 |
| kwh per year | | | 1349040000 |
| **Energy Costs per year** | | | **$ 404'712'000.00** |
| M2 PV Stations | 16000 | 20000 | 16000.00 |
| M2 PV Stations | 16000 | 20000 | 16000.00 |
| Total m2 Stations | | | 32000.00 |
| m2 PV Track | | | 2887500 |
| Total m2 PV | | | 2919500.00 |
| kwh PV per year per m2 | 150 | 230 | 230 |
| **Total Costs saved with PV** | | | **$ 201'445'500.00** |
| **Resulting Energy Costs** | | | **$ 203'266'500.00** |
| Insurance costs per km per | 0.0075 | 0.011 | 0.0075 |
| **Insurance** | | | **$ 60'706'800.00** |
| **Sales and Marketing** | 16000000 | 38000000 | **$ 16'000'000.00** |
| **Total Variable Costs per year** | | | **366'697'300.00 CHF** |

| **Total Operating costs per year** | **530'697'300.00 CHF** |
|---|---|

| Name | Baseline | 550 | 600 | 25 | 50 | 75 | 50 | 100 | 28 | 60 | 365 24 2 | 265 18 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| operating days | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | **365** | **365** |
| operating hours | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | **24** | **18** |
| operatin min | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | **1440** | **432** |
| departure frequency | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | **2** | **5** |
| cruising speed | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 | 700.00 |
| acceleration G | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| acceleration m/s^2 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 |
| distance | 550.00 | **550.00** | **600.00** | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 |
| tunnel | 25.00 | 25.00 | 25.00 | **25.00** | **50.00** | **75.00** | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| pillar | 75.00 | 75.00 | 75.00 | **75.00** | **50.00** | **25.00** | 75.00 | 75.00 | 75.00 | 75.00 | 75.00 | 75.00 |
| pillar spacing | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| pump frecuency | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| preassure | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| tube diameter | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 |
| Emergency Exit | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
| Siwss | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| France | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| land to buy | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | **50.00** | **100.00** | 50.00 | 50.00 | 50.00 | 50.00 |
| Passengers | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | **28** | **60** | 28 | 28 |
| Regenerative braking | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| Capsule weight | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Capsules | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| Number of Tubes | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Track width | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| **Fixed Costs** | | | | | | | | | | | | |
| Service Administration | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 | 40000000 |
| Track & ROW Maintena | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 | 120000000 |
| Station Costs | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 | 4000000 |
| **Total Fixed Costs per ye** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** | **164’000’000.00 CHF** |
| **Variable Costs** | | | | | | | | | | | | |
| Equipment Maintenanc | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF | 0.30 CHF |
| **Equipment Maintenanc** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **94’608’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **86’724’000.00 CHF** | **26’017’200.00 CHF** |
| Energy per km per pers | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Costs per kWh | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| km per persone per yea | 8094240000 | 8094240000 | 8830080000 | 8094240000 | 8094240000 | 8094240000 | 8094240000 | 8094240000 | 8094240000 | 17344800000 | 8094240000 | 2428272000 |
| MJ per persone per km | 4856544000 | 4856544000 | 5298048000 | 4856544000 | 4856544000 | 4856544000 | 4856544000 | 4856544000 | 4856544000 | 10406880000 | 4856544000 | 1456963200 |
| MJ in kWh | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 |
| kwh per year | 1349040001 | 1349040001 | 1471680001 | 1349040001 | 1349040001 | 1349040001 | 1349040001 | 1349040001 | 1349040001 | 2890800002 | 1349040001 | 404712000.3 |
| **Energy Costs per year** | **$ 404’712’000.32** | **$ 404’712’000.32** | **$ 441’504’000.35** | **$ 404’712’000.32** | **$ 404’712’000.32** | **$ 404’712’000.32** | **$ 404’712’000.32** | **$ 404’712’000.32** | **$ 404’712’000.32** | **$ 867’240’000.69** | **$ 404’712’000.32** | **$ 121’413’600.10** |
| M2 PV Stations | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 |
| M2 PV Stations | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 |
| Total m2 Stations | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 | 32000.00 |
| m2 PV Track | 2887500 | 2887500 | 3150000 | 2887500 | 1925000 | 962500 | 2887500 | 2887500 | 2887500 | 2887500 | 2887500 | 2887500 |
| Total m2 PV | 2919500.00 | 2919500.00 | 3182000.00 | 2919500.00 | 1957000.00 | 994500.00 | 2919500.00 | 2919500.00 | 2919500.00 | 2919500.00 | 2919500.00 | 2919500.00 |
| kwh PV per year per m2 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 | 230 |
| **Total Costs saved with** | **$ 201’445’500.00** | **$ 201’445’500.00** | **$ 219’558’000.00** | **$ 201’445’500.00** | **$ 135’033’000.00** | **$ 68’620’500.00** | **$ 201’445’500.00** | **$ 201’445’500.00** | **$ 201’445’500.00** | **$ 201’445’500.00** | **$ 201’445’500.00** | **$ 201’445’500.00** |
| Insurance costs per km | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 | 0.0075 |
| **Total Insurance costs pe** | **$ 60’706’800.00** | **$ 60’706’800.00** | **$ 66’225’600.00** | **$ 60’706’800.00** | **$ 60’706’800.00** | **$ 60’706’800.00** | **$ 60’706’800.00** | **$ 60’706’800.00** | **$ 60’706’800.00** | **$ 130’086’000.00** | **$ 60’706’800.00** | **$ 18’212’040.00** |
| **Sales and Marketing** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** | **$ 16’000’000.00** |
| **Total Variable Costs pe** | **366’697’300.32 CHF** | **366’697’300.32 CHF** | **398’779’600.35 CHF** | **366’697’300.32 CHF** | **433’109’800.32 CHF** | **499’522’300.32 CHF** | **366’697’300.32 CHF** | **366’697’300.32 CHF** | **366’697’300.32 CHF** | **898’604’500.69 CHF** | **366’697’300.32 CHF** | **-19’802’659.90 CHF** |
| **Total Operating costs p** | **530’697’300.32 CHF** | **530’697’300.32 CHF** | **562’779’600.35 CHF** | **530’697’300.32 CHF** | **597’109’800.32 CHF** | **663’522’300.32 CHF** | **530’697’300.32 CHF** | **530’697’300.32 CHF** | **530’697’300.32 CHF** | **1’062’604’500.69 CHF** | **530’697’300.32 CHF** | **144’197’340.10 CHF** |

| Name | Baseline | 550 | 600 | 25 | 50 | 75 | 50 | 100 | 28 | 60 | 365 24 2 | 265 18 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| operating days | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | **365** | **365** |
| operating hours | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | **24** | **18** |
| departure frequency | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | **2** | **5** |
| cruising speed | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 |
| acceleration G | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| acceleration m/s^2 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 |
| distance | 550.00 | **550.00** | **600.00** | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 | 550.00 |
| tunnel | 25.00 | 25.00 | 25.00 | **25.00** | **50.00** | **75.00** | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| pillar | 75.00 | 75.00 | 75.00 | **75.00** | **50.00** | **25.00** | 75.00 | 75.00 | 75.00 | 75.00 | 75.00 | 75.00 |
| pillar spacing | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| pump frecuency | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| preassure | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| tube diameter | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 |
| Emergency Exit | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
| Siwss | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| France | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| land to buy | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | **50.00** | **100.00** | 50.00 | 50.00 | 50.00 | 50.00 |
| Passengers | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | **28** | **60** | 28 | 28 |
| Regenerative braking | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| Capsule weight | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Capsules | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| Number of Tubes | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Track width | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stations | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Station costs | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 | $130'000'000 |
| **2 Station costs** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** | **$260'000'000.00** |
| Square meter price Sw | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 |
| Square meter price Fr | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 | $8'000 |
| Square meter Swiss | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 |
| Square meter France | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 | 16000.00 |
| Land Station Zurich | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 | $124'800'000.00 |
| Land Station Paris | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 | $128'000'000.00 |
| **Total land Station** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** | **$252'800'000.00** |
| Chamber Zurich | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 | 4848888.00 |
| Chamber Paris | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 | 4840000.00 |
| **Total Chambers** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** | **9688888.00** |
| PV per m^2 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 | 280.00 |
| **Costs PV** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** | **8960000** |
| **Total Station Costs** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** | **$531'448'888.00** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tube per km | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 | $10'000'000.00 |
| **Cost Tube** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$6'000'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** | **$5'500'000'000.00** |
| Pillar per km | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 | $4'000'000.00 |
| **Cost Pillar** | **$1'650'000'000.00** | **$1'650'000'000.00** | **$1'800'000'000.00** | **$1'650'000'000.00** | **$1'100'000'000.00** | **$550'000'000.00** | **$1'650'000'000.00** | **$1'650'000'000.00** | **$1'650'000'000.00** | **$1'650'000'000.00** | **$1'650'000'000.00** | **$1'650'000'000.00** |
| Tunnel per km | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 | $70'000'000.00 |
| **Cost Tunnel** | **$9'625'000'000.00** | **$9'625'000'000.00** | **$10'500'000'000.00** | **$9'625'000'000.00** | **$19'250'000'000.00** | **$28'875'000'000.00** | **$9'625'000'000.00** | **$9'625'000'000.00** | **$9'625'000'000.00** | **$9'625'000'000.00** | **$9'625'000'000.00** | **$9'625'000'000.00** |
| Emergency Exit per km | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 |
| **EX Costs** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'110'000'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** | **$1'017'500'000.00** |
| Number of pumps | 110 | 110 | 120 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 |
| Pump cost | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 |
| **Total Pump Cost** | **$8'250'000.00** | **$8'250'000.00** | **$9'000'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** | **$8'250'000.00** |
| Square meter swiss | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 |
| Square meter france | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 |
| **ROW** | **$5'445'000'000.00** | **$5'445'000'000.00** | **$5'940'000'000.00** | **$5'445'000'000.00** | **$5'445'000'000.00** | **$5'445'000'000.00** | **$5'445'000'000.00** | **$10'890'000'000.00** | **$5'445'000'000.00** | **$5'445'000'000.00** | **$5'445'000'000.00** | **$5'445'000'000.00** |
| **PV** | **$808'500'000.00** | **$808'500'000.00** | **$882'000'000.00** | **$808'500'000.00** | **$539'000'000.00** | **$269'500'000.00** | **$808'500'000.00** | **$808'500'000.00** | **$808'500'000.00** | **$808'500'000.00** | **$808'500'000.00** | **$808'500'000.00** |
| Propulsion / Levitation | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 |
| **Propulsion / Levitation** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'396'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** | **$3'113'000'000.00** |
| **Total Track** | **$27'167'250'000.00** | **$27'167'250'000.00** | **$29'637'000'000.00** | **$27'167'250'000.00** | **$35'972'750'000.00** | **$44'778'250'000.00** | **$27'167'250'000.00** | **$32'612'250'000.00** | **$27'167'250'000.00** | **$27'167'250'000.00** | **$27'167'250'000.00** | **$27'167'250'000.00** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cpasule per seat | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 | $100'000.00 |
| Capsule cost | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $2'800'000.00 | $6'000'000.00 | $2'800'000.00 | $2'800'000.00 |
| **Total Capsule Costs** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$210'000'000.00** | **$450'000'000.00** | **$210'000'000.00** | **$210'000'000.00** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total** | **$27'908'698'888.00** | **$27'908'698'888.00** | **$30'378'448'888.00** | **$27'908'698'888.00** | **$36'714'198'888.00** | **$45'519'698'888.00** | **$27'908'698'888.00** | **$33'353'698'888.00** | **$27'908'698'888.00** | **$28'148'698'888.00** | **$27'908'698'888.00** | **$27'908'698'888.00** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soft costs | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| **Total Soft Costs** | $7'256'261'710.88 | $7'256'261'710.88 | $7'898'396'710.88 | $7'256'261'710.88 | $9'545'691'710.88 | $11'835'121'710.88 | $7'256'261'710.88 | $8'671'961'710.88 | $7'256'261'710.88 | $7'318'661'710.88 | $7'256'261'710.88 | $7'256'261'710.88 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Contingemcy | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| **Total contingency** | $3'628'130'855.44 | $3'628'130'855.44 | $3'949'198'355.44 | $3'628'130'855.44 | $4'772'845'855.44 | $5'917'560'855.44 | $3'628'130'855.44 | $4'335'980'855.44 | $3'628'130'855.44 | $3'659'330'855.44 | $3'628'130'855.44 | $3'628'130'855.44 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total Capital Costs** | **$38'793'091'454.32** | **$38'793'091'454.32** | **$42'226'043'954.32** | **$38'793'091'454.32** | **$51'032'736'454.32** | **$63'272'381'454.32** | **$38'793'091'454.32** | **$46'361'641'454.32** | **$38'793'091'454.32** | **$39'126'691'454.32** | **$38'793'091'454.32** | **$38'793'091'454.32** |
| **Total Capital Costs per** | **$70'532'893.55** | **$70'532'893.55** | **$70'376'739.92** | **$70'532'893.55** | **$92'786'793.55** | **$115'040'693.55** | **$70'532'893.55** | **$84'293'893.55** | **$70'532'893.55** | **$71'139'439.01** | **$70'532'893.55** | **$70'532'893.55** |

| Name | Min. | Max. | CurVal. | CurVal. | CurVal. | CurVal. | CurVal. | CurVal. | CurVal. | CurVal. |
|---|---|---|---|---|---|---|---|---|---|---|
| operating days | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 |
| operating hours | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| operatin min | | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 | 1440 |
| departure frequency | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| cruising speed | 700 | 1000 | 825.62 | 702.68 | 898.85 | 872.33 | 947.45 | 983.76 | 954.63 | 928.38 |
| acceleration G | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| acceleration m/s^2 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 |
| distance | 550 | 600 | 589.80 | 579.67 | 556.24 | 598.97 | 559.38 | 556.05 | 557.98 | 586.56 |
| tunnel | 25 | 75 | 46.08 | 53.72 | 64.72 | 71.62 | 30.00 | 35.83 | 52.88 | 35.01 |
| pillar | 25 | 75 | 53.92 | 46.28 | 35.28 | 28.38 | 70.00 | 64.17 | 47.12 | 64.99 |
| pillar spacing | 25 | 30 | 28.57 | 25.09 | 25.08 | 27.04 | 25.78 | 27.99 | 25.71 | 26.03 |
| pump frecuency | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| preassure | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| tube diameter | 3.5 | 4 | 3.84 | 3.72 | 3.65 | 3.76 | 3.94 | 3.52 | 3.91 | 3.92 |
| Emergency Exit | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
| Siwss | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| France | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| land to buy | 50 | 100 | 57.25 | 84.63 | 51.60 | 52.39 | 55.88 | 92.91 | 91.12 | 95.55 |
| Passengers | 28 | 60 | 47 | 53 | 57 | 31 | 50 | 29 | 35 | 29 |
| Regenerative braking | 80 | 90 | 87 | 88 | 83 | 84 | 82 | 81 | 83 | 88 |
| Capsule weight | 15 | 26 | 25 | 24 | 18 | 24 | 23 | 16 | 16 | 17 |
| Capsules | 75 | 100 | 99 | 91 | 79 | 99 | 99 | 89 | 93 | 89 |
| Number of Tubes | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Track width | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| **Fixed Costs** | | | | | | | | | | |
| Service Administration | 40000000 | 70000000 | 42204779.8 | 46681732.5 | 58744023.46 | 55106673.1 | 60435946.23 | 46060695.06 | 43281392.24 | 43901071.45 |
| Track & ROW Maintenance | 120000000 | 180000000 | 174076364.8 | 155088871.5 | 125168871 | 174895282.9 | 122423462.8 | 162757568.5 | 130160874.1 | 127504353.2 |
| Station Costs | 4000000 | 20000000 | 18206339.43 | 10369093.6 | 12907606.65 | 15609604.26 | 7271895.32 | 19105272.55 | 4509317.669 | 13350457.57 |
| **Total Fixed Costs per year** | | | **234’487’484.08 CHF** | **212’139’697.61 CHF** | **196’820’501.15 CHF** | **245’611’560.26 CHF** | **190’131’304.33 CHF** | **227’923’536.11 CHF** | **177’951’584.03 CHF** | **184’755’882.21 CHF** |
| **Variable Costs** | | | | | | | | | | |
| Equipment Maintenance per km | 0.3 | 0.8 | 0.46 CHF | 0.69 CHF | 0.64 CHF | 0.60 CHF | 0.64 CHF | 0.75 CHF | 0.78 CHF | 0.62 CHF |
| **Equipment Maintenance** | | | **141’835’789.28 CHF** | **210’501’505.53 CHF** | **187’498’998.32 CHF** | **189’346’703.78 CHF** | **188’441’315.97 CHF** | **218’068’933.74 CHF** | **227’473’016.65 CHF** | **192’305’102.07 CHF** |
| Energy per km per person in MJ | 0.6 | 0.7 | 0.634609329 | 0.666328736 | 0.698415195 | 0.689842997 | 0.658730021 | 0.618942346 | 0.605577645 | 0.698059728 |
| Costs per kWh | | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| km per persone per year | | | 14464136071 | 16189770362 | 16645687191 | 9855295152 | 14562626003 | 8335532067 | 10287995434 | 8888196036 |
| MJ per persone per km per year | | | 9179075691 | 10787709216 | 11625600869 | 6798606347 | 9592838939 | 5159213769 | 6230180049 | 6204491707 |
| MJ in kWh | | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 | 0.277777778 |
| kwh per year | | | 2549743248 | 2996585893 | 3229333575 | 1888501763 | 2664677483 | 1433114936 | 1730605569 | 1723469919 |
| **Energy Costs per year** | | | **$ 764’922’974.27** | **$ 898’975’767.97** | **$ 968’800’072.44** | **$ 566’550’528.88** | **$ 799’403’244.88** | **$ 429’934’480.77** | **$ 519’181’670.72** | **$ 517’040’975.62** |
| M2 PV Stations | 16000 | 20000 | 19278.95 | 19498.40 | 16402.90 | 19810.92 | 17291.85 | 16808.52 | 19916.35 | 19418.05 |
| M2 PV Stations | 16000 | 20000 | 16613.61 | 17973.58 | 17724.35 | 17762.78 | 18695.29 | 18223.44 | 18884.77 | 18969.84 |
| Total m2 Stations | | | 35892.56 | 37471.98 | 34127.26 | 37573.70 | 35987.15 | 35031.96 | 38801.12 | 38387.89 |
| m2 PV Track | | | 2441588.545 | 1996379.116 | 1432737.976 | 1278075.56 | 3088890.968 | 2513597.407 | 2058787.568 | 2985173.97 |
| Total m2 PV | | | 2477481.10 | 2033851.09 | 1466865.23 | 1315649.26 | 3124878.12 | 2548629.37 | 2097588.69 | 3023561.86 |
| kwh PV per year per m2 | 150 | 230 | 175.5929971 | 212.4157187 | 155.5470202 | 195.8139351 | 187.7723139 | 153.7517692 | 164.6838419 | 179.5668585 |
| **Total Costs saved with PV** | | | **$ 130’508’499.64** | **$ 129’606’582.55** | **$ 68’449’954.80** | **$ 77’286’737.78** | **$ 176’029’678.35** | **$ 117’556’882.20** | **$ 103’631’689.11** | **$ 162’879’451.38** |
| Insurance costs per km per passenger | 0.0075 | 0.011 | 0.00936153 | 0.0087167 | 0.009251798 | 0.010019706 | 0.010169644 | 0.007831124 | 0.010527897 | 0.008743576 |
| **Total Insurance costs per year** | | | **$ 135’406’450.20** | **$ 141’121’364.42** | **$ 154’002’539.62** | **$ 98’747’159.26** | **$ 148’096’716.34** | **$ 65’276’586.51** | **$ 108’310’959.76** | **$ 77’714’617.26** |
| **Sales and Marketing** | 16000000 | 38000000 | **$ 30’625’416.90** | **$ 17’188’705.13** | **$ 23’392’689.72** | **$ 36’270’586.30** | **$ 19’297’680.84** | **$ 35’452’107.04** | **$ 27’701’524.95** | **$ 18’288’341.16** |
| **Total Variable Costs per year** | | | **942’282’131.01 CHF** | **1’138’180’760.50 CHF** | **1’265’244’345.30 CHF** | **813’628’240.44 CHF** | **979’209’279.67 CHF** | **631’175’225.85 CHF** | **779’035’482.97 CHF** | **642’469’584.72 CHF** |
| **Total Operating costs per year** | | | **1’176’769’615.09 CHF** | **1’350’320’458.11 CHF** | **1’462’064’846.46 CHF** | **1’059’239’800.71 CHF** | **1’169’340’583.99 CHF** | **859’098’761.97 CHF** | **956’987’067.01 CHF** | **827’225’466.93 CHF** |
| | | Simulations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

| Name | Min. | Max. | CurVal. | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| operating days | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 | 365 |
| operating hours | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| departure frequency | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| cruising speed | 700 | 1000 | 717.02 | 817.82 | 800.21 | 813.57 | 897.90 | 915.79 | 870.15 | 817.77 |
| acceleration G | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| acceleration m/s^2 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 |
| distance | 550 | 600 | 560.55 | 572.10 | 595.17 | 599.51 | 572.57 | 575.32 | 579.52 | 554.20 |
| tunnel | 25 | 75 | 27.19 | 30.46 | 51.31 | 33.93 | 60.77 | 69.05 | 29.96 | 58.77 |
| pillar | 25 | 75 | 72.81 | 69.54 | 48.69 | 66.07 | 39.23 | 30.95 | 70.04 | 41.23 |
| pillar spacing | 25 | 30 | 29.53 | 26.38 | 28.04 | 28.86 | 29.88 | 29.65 | 29.66 | 26.57 |
| pump frecuency | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| preassure | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| tube diameter | 3.5 | 4 | 3.68 | 3.59 | 3.51 | 3.72 | 3.56 | 3.79 | 3.80 | 3.93 |
| Emergency Exit | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
| Siwss | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| France | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| land to buy | 50 | 100 | 65.39 | 98.75 | 83.86 | 56.68 | 91.52 | 61.27 | 77.01 | 60.62 |
| Passengers | 28 | 60 | 32 | 29 | 43 | 42 | 50 | 59 | 56 | 33 |
| Regenerative braking | 80 | 90 | 80 | 84 | 86 | 89 | 87 | 85 | 81 | 88 |
| Capsule weight | 15 | 26 | 20 | 21 | 20 | 18 | 21 | 15 | 20 | 17 |
| Capsules | 75 | 100 | 77 | 91 | 76 | 84 | 81 | 91 | 88 | 78 |
| Number of Tubes | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Track width | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Stations | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Station costs | $130'000'000.00 | $180'000'000.00 | $175'168'299 | $133'284'282 | $151'274'677 | $160'793'376 | $139'448'588 | $173'828'098 | $172'906'222 | $164'318'644 |
| **2 Station costs** | | | **$350'336'598.76** | **$266'568'563.20** | **$302'549'353.68** | **$321'586'752.26** | **$278'897'175.72** | **$347'656'195.36** | **$345'812'444.72** | **$328'637'288.82** |
| Square meter price Swiss | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 | 7800 |
| Square meter price France | 8000 | 9000 | $8'492 | $8'325 | $8'171 | $8'511 | $8'048 | $8'392 | $8'298 | $8'731 |
| Square meter Swiss | 16000 | 20000 | 17236.09 | 19837.19 | 18251.32 | 16241.70 | 18299.00 | 19578.74 | 16117.88 | 18836.54 |
| Square meter France | 16000 | 20000 | 18768.49 | 17711.48 | 16724.12 | 17966.55 | 19396.61 | 17988.07 | 18010.60 | 16218.20 |
| Land Station Zurich | | | $134'441'506.50 | $154'730'072.93 | $142'360'308.03 | $126'685'252.89 | $142'732'216.03 | $152'714'185.93 | $125'719'482.43 | $146'924'992.38 |
| Land Station Paris | | | $159'384'081.81 | $147'439'667.62 | $136'656'271.31 | $152'904'850.69 | $156'105'803.42 | $150'949'839.79 | $149'447'432.96 | $141'601'684.91 |
| **Total land Station** | | | **$293'825'588.31** | **$302'169'740.54** | **$279'016'579.34** | **$279'590'103.58** | **$298'838'019.46** | **$303'664'025.72** | **$275'166'915.39** | **$288'526'677.28** |
| Chamber Zurich | 4840000 | 17000000 | 6271910.99 | 7080418.48 | 13582949.65 | 12406508.70 | 16638357.24 | 10391232.85 | 15970087.88 | 9508304.96 |
| Chamber Paris | 4840000 | 17000000 | 11945346.20 | 12310164.17 | 6372300.39 | 16556803.76 | 16898376.64 | 12897632.98 | 8348446.01 | 6613735.24 |
| **Total Chambers** | | | **18217257.19** | **19390582.65** | **19955250.05** | **28963312.46** | **33536733.88** | **23288865.83** | **24318533.89** | **16122040.20** |
| PV per m^2 | 280 | 335 | 291.78 | 282.91 | 331.40 | 296.47 | 293.74 | 298.57 | 313.05 | 301.50 |
| **Costs PV** | | | **10505394.3** | **10622844.35** | **11590941.71** | **10141863.5** | **11072856.34** | **11216316.25** | **10683877.63** | **10568869.56** |
| **Total Station Costs** | | | **$672'884'838.56** | **$598'751'730.75** | **$613'112'124.77** | **$640'282'031.81** | **$622'344'785.39** | **$685'825'403.16** | **$655'981'771.63** | **$643'854'875.87** |
| Tube per km | $10'000'000.00 | $15'000'000.00 | $12'405'487.84 | $11'421'523.14 | $14'200'545.10 | $10'256'388.91 | $10'899'454.46 | $14'901'076.34 | $11'019'381.53 | $14'088'726.08 |
| **Cost Tube** | | | **$6'953'954'871.18** | **$6'534'276'190.48** | **$8'451'801'982.84** | **$6'148'776'540.47** | **$6'240'738'613.23** | **$8'572'899'952.42** | **$6'385'931'983.33** | **$7'808'041'612.41** |
| Pillar per km | $4'000'000.00 | $8'000'000.00 | $5'171'678.94 | $7'960'311.79 | $5'814'522.61 | $4'665'978.98 | $4'435'427.10 | $4'656'754.66 | $5'112'796.57 | $4'158'205.08 |
| **Cost Pillar** | | | **$2'110'782'415.43** | **$3'166'959'749.10** | **$1'684'924'459.62** | **$1'848'034'434.56** | **$996'288'838.46** | **$829'092'741.71** | **$2'075'251'349.46** | **$950'254'453.11** |
| Tunnel per km | $70'000'000.00 | $80'000'000.00 | $77'228'168.14 | $74'871'340.71 | $75'644'896.50 | $75'247'244.34 | $71'442'949.42 | $75'300'407.13 | $72'620'215.60 | $74'475'862.15 |
| **Cost Tunnel** | | | **$11'770'510'610.16** | **$13'046'953'650.35** | **$23'101'636'295.88** | **$15'308'390'971.88** | **$24'858'771'549.11** | **$29'915'343'015.00** | **$12'608'655'602.92** | **$24'255'283'019.50** |
| Emergency Exit per km | | 1850000 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 | $1'850'000.00 |
| **EX Costs** | | | **$1'037'026'248.58** | **$1'058'388'693.57** | **$1'101'072'779.45** | **$1'109'087'877.08** | **$1'059'260'945.35** | **$1'064'343'578.45** | **$1'072'108'642.28** | **$1'025'279'141.52** |
| Number of pumps | | | 112 | 114 | 119 | 120 | 115 | 115 | 116 | 111 |
| Pump cost | | 75000 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 | $75'000.00 |
| **Total Pump Cost** | | | **$8'408'320.93** | **$8'581'529.95** | **$8'927'617.13** | **$8'992'604.41** | **$8'588'602.26** | **$8'629'812.80** | **$8'692'772.78** | **$8'313'074.12** |
| Square meter swiss | | 900 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 | $900.00 |
| Square meter france | | 600 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 | $600.00 |
| **ROW** | | | **$7'258'083'360.96** | **$11'186'024'151.03** | **$9'882'965'079.48** | **$6'728'241'168.43** | **$10'375'494'573.86** | **$6'979'269'013.92** | **$8'836'635'334.22** | **$6'652'002'652.72** |
| **PV** | | | **$876'026'270.72** | **$807'060'981.02** | **$673'665'448.00** | **$873'234'841.26** | **$469'441'967.52** | **$402'712'947.53** | **$966'356'709.85** | **$542'128'683.14** |
| Propulsion / Levitation per km | | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 | 2830000 |
| **Propulsion / Levitation costs** | | | **$3'172'739'765.91** | **$3'238'097'300.32** | **$3'368'687'530.65** | **$3'393'209'396.91** | **$3'240'765'919.29** | **$3'256'316'029.20** | **$3'280'072'927.20** | **$3'136'799'968.09** |
| **Total Track** | | | **$33'187'531'863.87** | **$39'046'342'245.82** | **$48'273'681'193.05** | **$35'417'967'835.01** | **$47'249'351'009.08** | **$51'028'607'091.03** | **$35'233'705'322.04** | **$44'378'102'604.60** |
| Cpasule per seat | 100000 | 150000 | $102'303.56 | $116'236.32 | $138'053.85 | $125'124.46 | $103'448.02 | $122'483.31 | $131'807.19 | $132'066.65 |
| Capsule cost | | | $3'295'878.40 | $3'347'129.88 | $5'867'968.12 | $5'252'268.90 | $5'182'923.09 | $7'282'084.54 | $7'375'754.52 | $4'354'976.76 |
| **Total Capsule Costs** | | | **$253'277'299.27** | **$304'319'746.58** | **$447'579'304.42** | **$443'761'608.10** | **$418'419'648.49** | **$662'881'947.77** | **$647'030'141.80** | **$338'459'943.56** |
| **Total** | | | **$34'113'694'001.70** | **$39'949'413'723.15** | **$49'334'372'622.24** | **$36'502'011'474.91** | **$48'290'115'442.97** | **$52'377'314'441.96** | **$36'536'717'235.47** | **$45'360'417'424.03** |
| Soft costs | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| **Total Soft Costs** | | | $8'869'560'440.44 | $10'386'847'568.02 | $12'826'936'881.78 | $9'490'522'983.48 | $12'555'430'015.17 | $13'618'101'754.91 | $9'499'546'481.22 | $11'793'708'530.25 |
| Contingemcy | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| **Total contingency** | | | $4'434'780'220.22 | $5'193'423'784.01 | $6'413'468'440.89 | $4'745'261'491.74 | $6'277'715'007.59 | $6'809'050'877.46 | $4'749'773'240.61 | $5'896'854'265.12 |
| **Total Capital Costs** | | | **$47'418'034'662.37** | **$55'529'685'075.18** | **$68'574'777'944.92** | **$50'737'795'950.12** | **$67'123'260'465.72** | **$72'804'467'074.33** | **$50'786'036'957.30** | **$63'050'980'219.40** |
| **Total Capital Costs per km** | | | **$84'591'266.85** | **$97'062'561.24** | **$115'217'941.60** | **$84'632'538.55** | **$117'230'822.50** | **$126'545'851.18** | **$87'634'932.38** | **$113'768'347.26** |
| | | Simulations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |