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Multi-Criteria Analysis of the proposed Hyperloop transport project in Northern Holland

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"The first step is to establish that something is possible; then probability will occur."

- Elon Musk

Abstract

New technological advancements such as the "Hyperloop" touted as "the fifth mode of transport" could be an answer to the problems ailing the current transport industry. Hyperloop consists of transport pods running through low pressure tubes for the high speed(upto 1000 km/hr) transportation of goods and people. This technology came into prominence after the open design concept "Hyperloop Alpha" was published by Musk (2013) and since then several governments, academia and private firms have shown interest in the technology with a few test tracks being built in the U.S and Europe. The first Hyperloop human passenger tests at 48m/s (173kmph) inside the vacuum tube were successfully carried out by Virgin Hyperloop at Las Vegas, U.S.A in November 2020 (Mlot, S., 2020). Hardt in collaboration with the Province of North Holland had published a concept study on the impact of 5 proposed Hyperloop routes in Northern Holland (Prov. N-Holland & Hardt, 2020). This research project explores the proposed Hyperloop transport solution in North Holland and its neighbouring areas from a social, socio-economic and environmental perspective as a comparison with existing rail and aviation transport alternatives. A Multi-Criteria Analysis of one of the proposed Hyperloop transport project routes was conducted as a comparison with existing rail and aviation transport alternatives. Results showed that Hyperloop was the highest ranked transport alternative overall in this study, closely followed by Rail, and Aviation was ranked last. Within the social criteria, Hyperloop was ranked best whereas within socio-economic and environmental criteria, Rail was ranked as the best alternative. This MCA could be useful as an aid to decision makers such as regional and national governments, transport policymakers or investors for any similar Hyperloop transport projects within Europe.

Keywords: Hyperloop • Multi-Criteria Analysis • Sustainable Transport • Fifth Mode of Transport • Emerging Technology

Sammanfattning

Nya tekniska framsteg som ”Hyperloop” som ”femte transportsättet” kan vara ett svar på de problem som drabbar den nuvarande transportbranschen. Hyperloop består av transportbälgen som går genom lågtrycksrör för transport av gods och människor med hög hastighet (upp till 1000 km / tim). Denna teknik kom till framträdande efter att det öppna designkonceptet ”Hyperloop Alpha” publicerades av Musk (2013) och sedan dess har flera regeringar, den akademiska världen och privata företag visat intresse för tekniken med några testspår som byggs i USA och Europa. De första Hyperloop-testningarna för mänskliga passagerare vid 48m / s (173kmph) inuti vakuumröret utfördes framgångsrikt av Virgin Hyperloop i Las Vegas, USA i november 2020 (Mlot, S., 2020). Hardt i samarbete med provinsen Nordholland hade publicerat en konceptstudie om effekterna av 5 föreslagna Hyperloop-rutter i norra Holland (Prov. N-Holland & Hardt, 2020). Detta forskningsprojekt utforskar den föreslagna Hyperloop-transportlösningen i Nordholland och dess närliggande områden ur ett socialt, socioekonomiskt och miljömässigt perspektiv som en jämförelse med befintliga tåg- och flygtransportalternativ. En multikriterieanalys av en av de föreslagna vägarna för Hyperloop-transportprojekt genomfördes som en jämförelse med befintliga järnvägs- och flygalternativ. Resultaten visade att Hyperloop var det högst rankade transportalternativet totalt sett i denna studie, tätt följt av Rail, och Aviation rankades sist. Inom de sociala kriterierna rankades Hyperloop bäst medan inom socioekonomiska och miljömässiga kriterier rankades Rail som det bästa alternativet. Denna MCA kan vara användbar som ett hjälpmedel för beslutsfattare som regionala och nationella regeringar, transportpolitiker eller investerare för liknande Hyperloop-transportprojekt inom Europa.

Nyckelord: Hyperloop • Flerkriterieanalys • Hållbar transport • Femte transportsättet • Emerging Technology

Forewords and Acknowledgements

This Degree Project in Strategies for Sustainable Development has been conducted as the completion of the Master's program in Sustainable Technology at KTH, The Royal Institute of Technology, Stockholm. Strategies for sustainable development is about analysing long-term solutions and developing knowledge concerning strategic sustainability problems. The subject is at the point of intersection between environmental issues, societal change and technological development. The master's programme in Sustainable Technology is based on the concept of industrial ecology with a focus on the understanding of interactions between technical, economic, social and ecological systems and processes. The project spanned from April to November 2020 and was written at the Department of Sustainable Development, Environmental Science and Engineering (SEED) at KTH. I would like to thank my supervisor Dr. Elisabeth Ekener for her valuable guidance during the course of this project. I would also like to thank Dr. Miguel Brandão for his inspiring lectures at KTH. I would also like to thank my managers and colleagues at work who have encouraged me to pursue my further education. Last but not the least I would like to thank my family for their continued support and encouragement.

List of Abbreviations

MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis (a form of MCA) (also known as Multi-Attribute Decision Analysis(MADA))
CBA	Cost-Benefit Analysis
LCA	Life Cycle Assessment
EIA	Environmental Impact Assessment
EHC	European Hyperloop Center
UN	United Nations
GHG	Greenhouse gases
SDGs	Sustainable Development Goals
ICE	InterCity Express (high speed train operated by Deutsche Bahn)
TRL	Technology Readiness Level
AMS	Amsterdam airport code
FRA	Frankfurt airport code
DUS	Düsseldorf airport code
EIN	Eindhoven airport code
CDG	Paris airport code
MRA	Metropolitan Region Amsterdam
TEN-T	Trans-European Transport Network

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1. Introduction

1.1 Background

Our current human civilization would be hard to imagine without modern transport. Right from the bed you woke up from today to the device on which you are reading this thesis, all aspects of our life including ourselves and the physical products that we consume require some kind of transport. The availability of or the lack of good transport alternatives could determine where you live and work, how much money you make and what social networks you are part of. Transporting goods and people has been one of the cornerstones of human civilization and the development of nations goes hand in hand with the development of speedy and reliable transport networks. Be it the highway and aviation network in the USA or the highly developed rail, road and aviation network in Europe, such transport networks have played a key role and in many cases have been a precursor to the economic and social development of these regions.

Aviation has brought cities and continents together thus contributing to significant economic and social development through the quick transport of people and goods. Bringing cities even more closer together through advanced transport systems might increase the overall economic efficiency of city pairs, enabling the easier movement of goods and people. Transport infrastructure development does not always evolve to solve the growing demand for transport but has been used by lawmakers to spark the growth and development of their region such as the EU Trans-European Transport Network (TEN-T) projects (Ferrari et al., 2018).

1.2 The current transport system

Existing road, rail and aviation networks with high travel times, increasing costs and high GHG emissions and noise pollution are unable to keep up with the growing demand. As per the 2017 figures, the transport sector contributes to 27 % of total EU GHG emissions (European Environment Agency, 2019) and reducing overall GHG emissions will not be possible without reducing transport related emissions. Water and road transport are relatively inexpensive to run but are time consuming with high emissions, rail transport is also relatively inexpensive and faster but expensive to build and maintain (Koerkamp, 2019). On the other hand, aviation transport being the fastest is both expensive and with high emissions. There is a growing “need for speed” and by 2050 it is projected that 41% of the world traffic share will be high-speed transport. However, there are some limitations to this growth such as the existing aviation infrastructure and congested air traffic space. (Schafer & Victor, 2000 cited in Decker et al., 2017)

Although the EU has been investing heavily on high speed rail lines, the result has been a lot of national lines not connected well with each other and with problems such as cost overruns and delayed construction (European Court of Auditors, 2018). In order to address all these concerns, a big leap in transportation technologies is required. The new technology needs to be fast, relatively inexpensive, accessible and least damaging to the environment. New technological advancements such as the “Hyperloop” could possibly be an answer to the problems ailing the existing transport industry.

1.3 Research Problem and Purpose

The report "Public Transport in 2040: Outlines of a Vision for the Future" was published together by The Ministry of Infrastructure and Water Management, 12 provincial authorities, the metropolitan regions of Amsterdam, Rotterdam, The Hague and few public transport companies suggest the importance of having a fast network to connect Netherlands to the main economic regions of neighbouring countries such as Germany, France, Belgium, UK (Ministry of Infrastructure and Water Management et al., 2019). The Dutch government has a target to reduce greenhouse gas emissions by 49% by 2030 and by 95% by 2050 from 1990 levels (Government of the Netherlands, 2020). A Hyperloop transport system will likely reduce the energy consumption and emissions of long-distance people transport, albeit by a few percent (van Goeverden, Janic & Milakis, 2018). The Hyperloop system was also found to be relatively more positive than high speed rail and airline transport in terms of lower energy consumption, GHG emissions and noise (Van Goeverden et al., 2018).

IATA has a target to reduce net aviation CO_2 emissions by 50% by 2050 from 2005 levels (IATA, 2020). There arises an opportunity to substitute some of the air passenger routes with Hyperloop. There has also been political willpower in Netherlands for the consideration of Hyperloop technology such as the excerpt from the Parliament letter "I believe further innovation in mobility is necessary to meet future challenges in terms of accessibility and sustainability in the Netherlands" by the then Minister of Infrastructure and the Environment (Tweede Kamer der Staten-Generaal, 2017) after which the (European Hyperloop Center (EHC)) is under construction (expected completion 2022) in the Dutch province of Groningen (EIT, 2020). There also have been a few studies comparing the Hyperloop with other alternatives (Van Goeverden, et al., 2018; Martínez-Díaz, Soriguera & Pérez, 2018; Van Goeverden, et al., 2017) as well as a MCA study by Janic (2018) comparing hyperloop with high speed rail and maglev for assumed track between Moscow and St. Petersburg.

In march 2020, Hardt in collaboration with the Province of North Holland published a concept study on the impact of Hyperloop on the development perspective. In this concept study, 5 different Hyperloop routes were proposed between different cities and the trip time savings versus rail, car and flight, the agglomeration benefits of bringing cities closer (improvements in accessibility, connectivity, substitution and decongestion) and the potential increase in GDP value was estimated (Prov. N-Holland & Hardt, 2020). However, the sustainability and climate action remained out of scope of that study and hence a holistic study was required to fill this gap.

The purpose of this study is to explore and increase the understanding of the Hyperloop alternative from multiple criterias as a comparison with existing transport alternatives. And from this, the following research questions were formed,
How could the hyperloop fare as compared to the existing transport alternatives in the North Holland region and nearby areas? How could the hyperloop perform from social, socio-economic and environmental perspectives?

The aim of this project was exploring the proposed Hyperloop transport solution in North Holland and its neighbouring areas from a social, socio-economic and environmental perspective as a comparison with existing transport alternatives. To be able to answer these questions, the objective of this study was to carry out a Multi-Criteria Analysis (MCA) comparing Hyperloop with existing transport alternatives and ranking them thus indicating within the boundaries of this project, the best overall transport solution for this region. This MCA could be useful as an aid to decision makers for the consideration of similar Hyperloop transport projects within Europe.

1.4 Boundaries and Delimitations

The system boundaries were defined by the process of eliminating available transport alternatives and transport routes in the region thus choosing a specific set of transport alternatives and a transport route for conducting the analysis. The process used for choosing the transport alternatives and the transport route is explained below.

Choice of Transport Alternatives

The transport alternatives compared to Hyperloop in the concept study (Prov. N-Holland & Hardt, 2020) were car, aviation and rail. The car transport alternative was excluded due the following reasons,
i. Cars fall under the category of personal transport which has a different level of comfort, convenience, last mile connectivity and cost hence it would be difficult to compare with the other public transport options such as hyperloop, aviation and rail.
ii. It is the stated objective of the EU for intercity travel of medium distance (both passengers and freight) to shift away from road transport by as much as 50% by the year 2050 (European Commission, 2011). Hence, Intercity Bus transport was also excluded as an alternative.

Hyperloop, rail and aviation, all forms of public transportation, suitable for long distance intercity travel and offering a very similar level of service thus increasing their comparability and hence they were the transport alternatives chosen for the MCA.

Alternative 1: Hyperloop
The Hyperloop alternative was defined as the proposed Hyperloop operating on Route 3 (Amsterdam - Utrecht - Eindhoven - Düsseldorf - Frankfurt) with stations at each of the 5 cities on the route (Prov. N-Holland & Hardt, 2020). Since Hyperloop is not yet in commercial operation, qualitative and quantitative data available from various published literature was used.

Alternative 2: Rail
Rail was defined as the high speed ICE (Intercity Express) trains running along Route 3. All stations except Eindhoven had ICE connectivity. For the connectivity of Eindhoven station to the other stations, regular speed NS Intercity trains were considered during comparison with the other alternatives.

Alternative 3: Aviation
The aviation alternative was defined as the commercial passenger flights operating between the airports of Amsterdam, Frankfurt, Eindhoven and Düsseldorf. There was no airport at Utrecht. Even though there are several international and intercontinental flights connecting to these 4 airports today, they were outside the system boundary for the aviation alternative which was restricted to flights operating between these 4 airports.

Choice of Transport Route

The 5 proposed routes in the concept study (Prov. N-Holland & Hardt, 2020) were as follows,
Route 1. Amsterdam - Leiden - Den Haag.
Route 2. Amsterdam - Rotterdam - Brussels - Paris.
Route 3. Amsterdam - Utrecht - Eindhoven - Düsseldorf - Frankfurt.
Route 4. Amsterdam - Amersfoort - Arnhem - Duisburg - Düsseldorf.
Route 5. Amsterdam - Almere - Lelystad - Zwolle - Groningen.
Carrying out a MCA on all the five proposed routes was not deemed feasible considering the limited time frame and resources of the project hence it was decided to select and carry out a MCA on only one of the proposed routes.

Route selection was based on the estimations on possible benefits of building the Hyperloop for each route as mentioned in the concept report (Prov. N-Holland & Hardt, 2020),
i. Estimated agglomeration benefits of Hyperloop for each route such as the benefits of households and businesses being closer to each other.
ii. Estimated percentage reduction of travel time for passengers of Hyperloop against aviation ,rail and car on the same route. Higher travel time savings were estimated for higher distance routes such as the international routes.
iii. Estimated substitution of flight passengers through introduction of Hyperloop for the airports on that route for example the route with higher flight passenger substitution was preferred with higher potential to decongest airspace and subsequently reducing flight emissions thereof.
iv. Higher number of airports along the route was preferred which could potentially have higher agglomeration benefits through connecting different aviation hubs and smaller airports.
v. National or International route? Higher distance international routes were preferred due to potential estimated higher travel time benefits, agglomeration benefits to build Hyperloop along these routes. Also, the proposed national routes did not connect two airports together so there were no estimated short haul airline passenger substitution and airport decongestion benefits.

Routes were eliminated one by one after brainstorming on the above criteria to reach the final route on which MCA was to be carried out. The two national routes(Route 1 & 5) were eliminated due to lack of estimated short haul airline passenger substitution and airport decongestion benefits. Out of the remaining three international routes, Route 4 was eliminated as it did not connect two aviation hubs. From the remaining two international routes, which were quite similar to each other, Route 2 was eliminated as it spanned across three countries (Netherlands, Belgium and France) which could face higher complexity in receiving approvals, regulations, negotiations and final implementation.

Route 3, which was the last remaining option, spans across only two countries (Netherlands and Germany) with relatively lesser perceived complexity than Route 2 which went through three countries. For Route 3, while Amsterdam and Frankfurt are european aviation hubs, Düsseldorf is a midsized airport and Eindhoven is a smaller airport. The hyperloop project could potentially improve the overall accessibility of the smaller towns along Route 3 and bring all the cities closer together. Considering all the above factors, *Route 3. Amsterdam - Utrecht - Eindhoven - Düsseldorf - Frankfurt* was perceived to be the most beneficial route among the five proposed Hyperloop routes and hence this was selected as the route for carrying out the MCA. The visual representation of the system boundary derived from the choice of transport alternatives and route is shown in Figure 1.

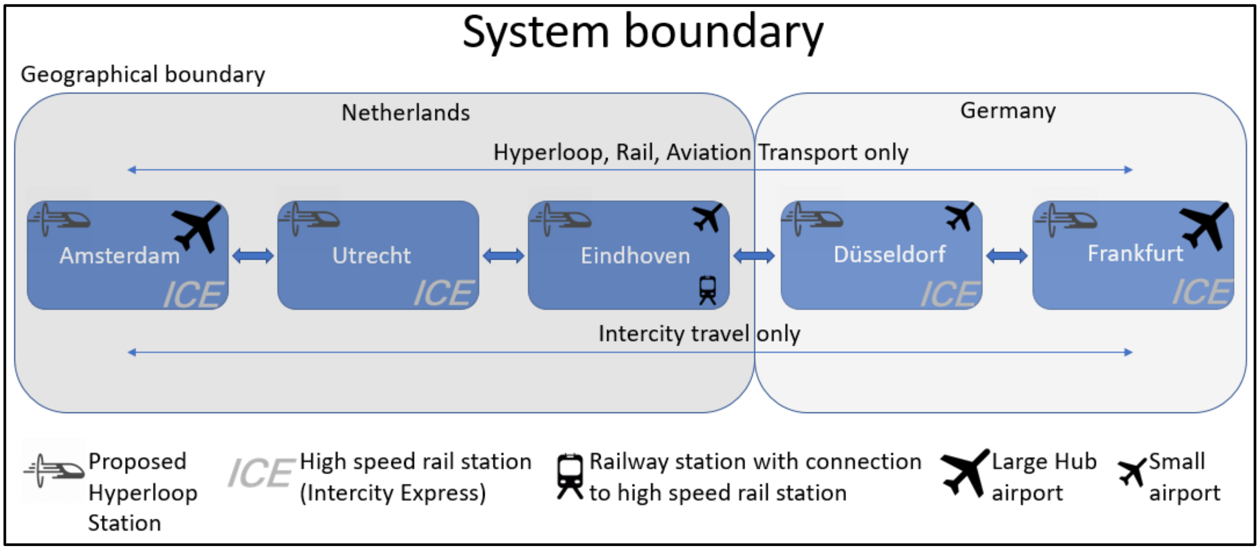

Figure 1: System boundary for the MCA showing transport alternatives, chosen route and geographical boundary.

This study was delimited to give an overview of the comparison of hyperloop with rail and aviation in the geographical urban area of the selected Hyperloop *Route 3. Amsterdam - Utrecht - Eindhoven - Düsseldorf - Frankfurt* and the transport of people within the said geographical urban area. Public transport projects are quite vast and complex in nature and it was not possible to consider all the aspects in this study. Only a small section of stakeholders' input could be included as a part of the MCA process, limiting the outcome of this study. The assessment of a new technology like Hyperloop had the added challenges of limited published research on the subject. The results of this study were delimited to function just as an aid to decision makers considering Hyperloop as a transport option in the North Holland region. The results could possibly also be extended to similar projects in Europe.

1.5 What is Hyperloop?

Hyperloop is the new potentially game changing transport technology often referred to as "the fifth mode of transport" which consists of transport pods running through low pressure tubes for the high speed transportation of goods and people. Even though the proposal for de-pressurized tubes transport has existed more than a century ago such as Robert Goddard's proposal for "Vactrain" (vacuum tube train) in 1904 and patent in 1950 cited in Schulz, et al., (2017) and the publication by Salter (1972). This technology came into prominence after the open design concept "Hyperloop Alpha" was published by Musk (2013).

Hyperloop has been proposed as a more cost efficient and faster alternative to high speed rail and aviation for distances upto 1500 km (European Commission, 2018). Hyperloop technology promises several benefits such as high speed, high carrying capacity, low operating expenses, all weather operation (Dudnikov, 2017). Since then, several companies have sprung up who are researching on creating a commercially feasible Hyperloop. Virgin Hyperloop One (with aim to provide Dubai with the world's first Hyperloop by 2021), Hyperloop Transportation Technologies and Hardt are a few of the companies leading the research and development around this technology (Arup et al., 2017). Some governments have shown interest in Hyperloop and a few test tracks are being built such as the test track in Toulouse, France built by Hyperloop Transportation Technologies (Schulz, 2019) and certification center and test track by Virgin Hyperloop One in the U.S. state of West Virginia (Johnson, 2020). Recently in Nov 2020, the first human passenger tests at 48m/s (173kmph) inside the vacuum tube were successfully carried out by Virgin Hyperloop at Las Vegas, U.S.A (Mlot, S., 2020). The photographs and the short description of the test pod can be seen in Figure 2.

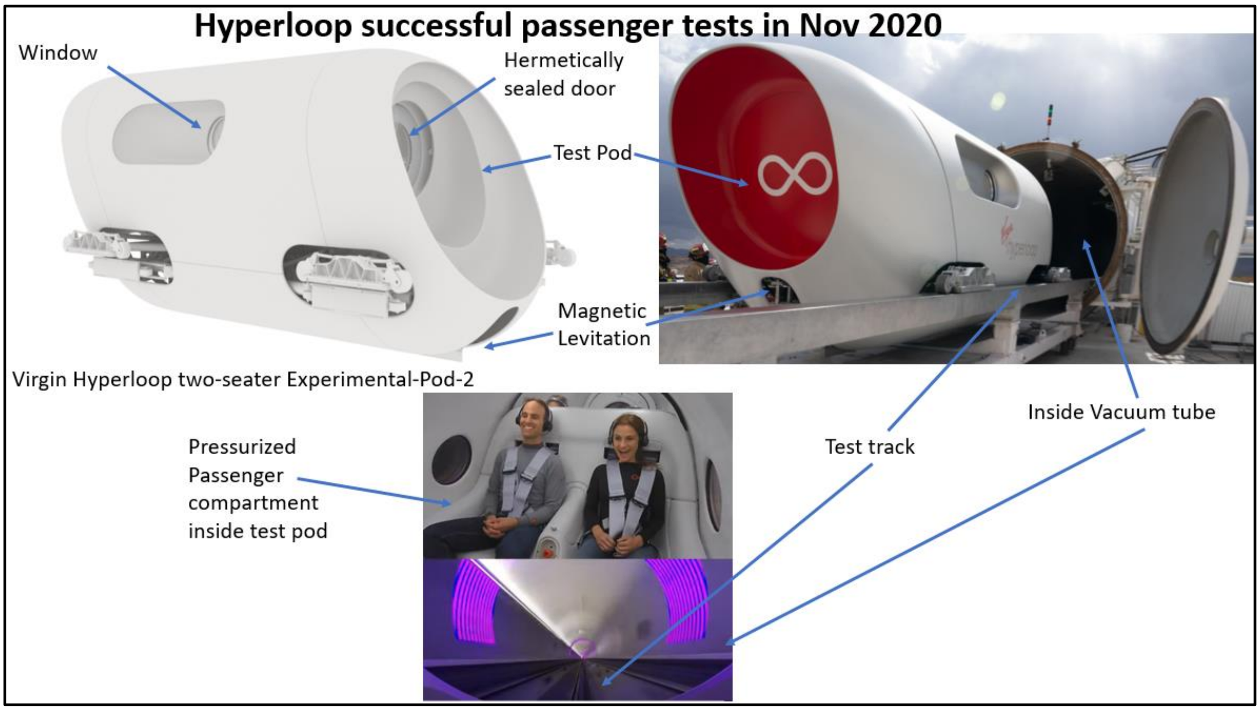

Figure 2: Hyperloop successful passenger tests conducted by Virgin Hyperloop in Nov 2020. Photographs source: Virgin Hyperloop (2020).

There has also been academic participation in the development of Hyperloop technology through the participation of several university teams competing for the Hyperloop pod competition that takes place annually since 2017 at the test track built by SpaceX in California (SpaceX, 2020). Students from TU Delft won the competition in 2017 (Pieters, 2017) and founded the company Hardt Hyperloop which has tested the technology on the 30m low speed test track in Delft (Pieters, 2019). A 3km high speed test track (European Hyperloop Center (EHC)) is under construction (expected completion 2022) in the Dutch province of Groningen (EIT, 2020).

The hyperloop system consists of pressurized pods travelling inside cylindrical vacuum tubes mounted on pillars on the ground or in a tunnel underground. Vacuum of approximately 100 Pascal pressure is maintained inside these tubes by the use of vacuum pumps. The reason to maintain vacuum inside the tube is to significantly reduce the air resistance when the pod travels at high speed inside the tube thus reducing the power consumption requirement. Hyperloop pods are

propelled at high speed using magnetic levitation created between the linear motor fixed inside the vacuum tube and the magnets which are mounted on top of the pod. The vacuum pumps and the linear motor are supposed to be powered by solar panels mounted on top of the vacuum tubes. (Musk, 2013 and Decker et al., 2017 cited in Janić, 2020)
The hyperloop way of working is explained in Figure 3.

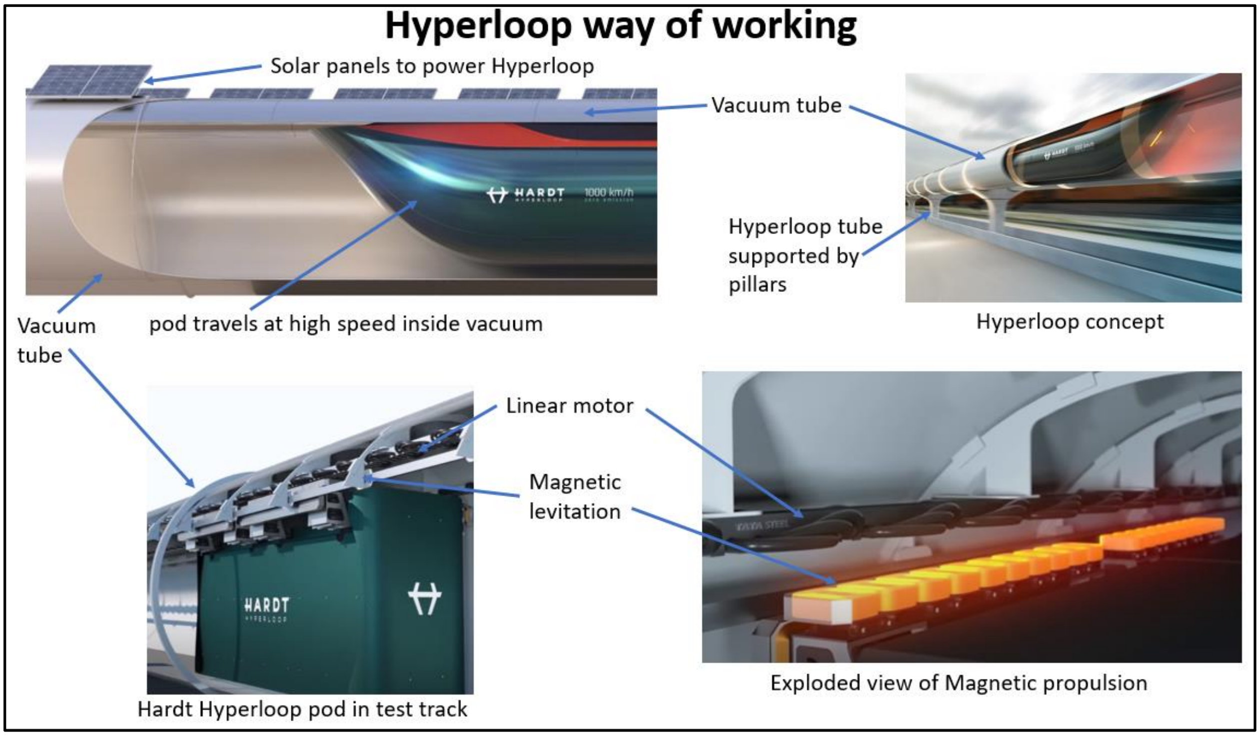

Figure 3: Hyperloop way of working. Concept images source: Hardt B.V. (2020).

The typical hyperloop station would consist of three sections; 1. Arrival chamber 2. Station chamber 3. Departure chamber. The hyperloop pod travelling from the vacuum tube track first arrives in the arrival chamber where the same level of vacuum is maintained as the vacuum tube track (approximately 100 Pascal). The track side door of the arrival chamber is closed and it is pressurized to ambient air pressure. Then the station side door of the chamber is opened and the pod moves to the station chamber. In this chamber, the doors of the pod open and the passengers can get on and off similar to a railway station. When the departing passengers are seated for the next journey, the doors of the pod are closed and the pod moves to the departure chamber. This is also at ambient air pressure. The doors of the departure chamber are closed and it is depressurized to the level of the vacuum tube track. Then the doors of the departure chamber are opened and the pod departs into the vacuum tube track towards its destination. (Musk, 2013 and Decker et al., 2017 cited in Janić, 2020)
The way of working of a typical Hyperloop station is described in Figure 4.

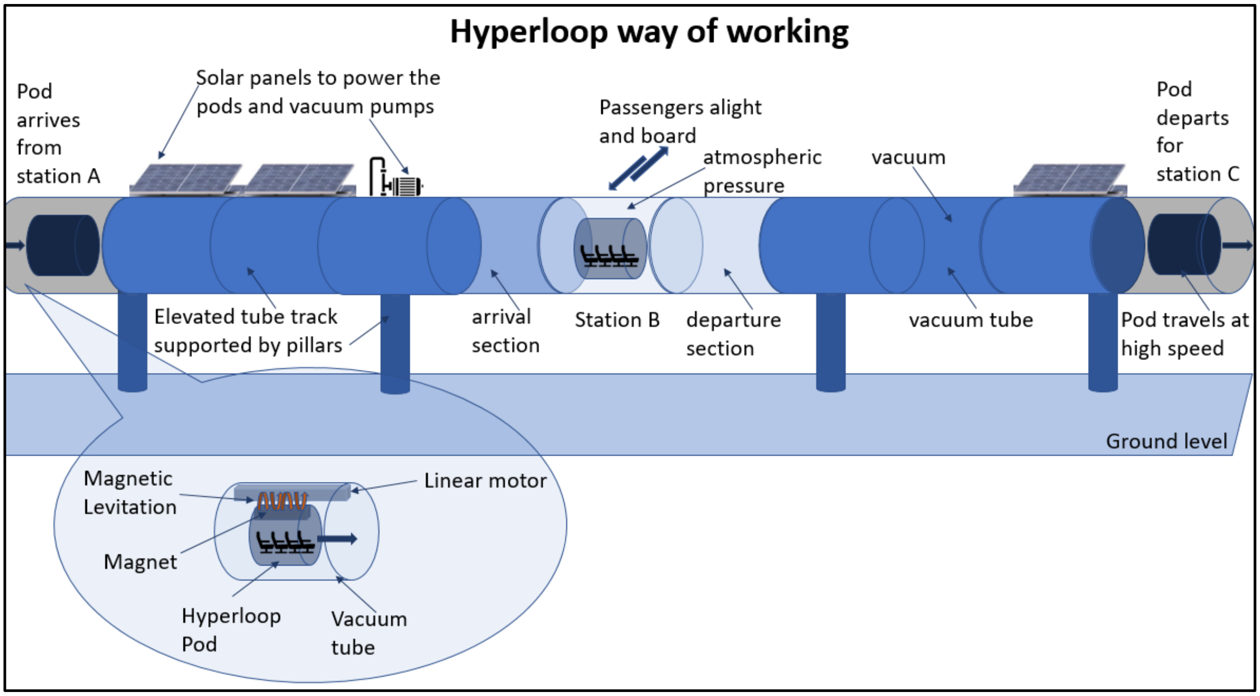

Figure 4: The Hyperloop way of working with a typical station based on concepts described by Musk (2013) and Decker et al. (2017) cited in Janić (2020).

2. Methods

Cost benefit analysis (CBA) has been widely used in support of the decision making process for transport projects. However, when it comes to the non-economic criteria such as noise, safety, emissions it becomes troublesome to apply CBA. Multi-Criteria Analysis (MCA) has appeared as an alternative to CBA inorder to deal with such problems. The decision making process also needs to include non economic aspects to support the decision making process. (Tudela, Akiki & Cisternas, 2006)

MCA could bring a degree of openness and structure to decision areas which are beyond the reach of CBA. MCA involves the establishing of objectives and criteria, and judgement of the performance of each alternative against each performance criterion and the application of weights to each criterion based on the different stakeholders to be able to rank the alternatives (Department for Communities and Local Government, 2009). Since the research question involved a new technology which is not yet in commercial operation with no finalized transport project and without a specific timeline or budget, and that a comparison with other existing transport alternatives in the region was required from varied criteria that could not be easily quantified monetarily such as noise, safety, emissions, equitable access and so on, hence MCA was chosen for this study.

A work plan was drafted in the form of a Gantt chart which contained the steps to carry out the MCA (refer appendix B). An extensive literature review of relevant peer reviewed scientific papers, journals, books and student theses was carried out. Hyperloop, rail and aviation related news articles, public and private company reports were also referred to. A Multi-Criteria Analysis (MCA) was carried out as per the MCA methods described by Mateo (2012), the MCA manual by the Department for Communities and Local Government (2009), book on MCDA methods by Triantaphyllou (2000) and also taking into account the review of the various MCA applications by Geneletti & Esmail (2018). The specific type of MCA used was Multi-Criteria Decision Analysis (MCDA) which is also known as Multi-Attribute Decision Analysis (MADA).

The MCA was carried out in 3 main stages as below defined by Geneletti & Esmail (2018) and Department for Communities and Local Government (2009),
i. Decision context: Establish aims, defining transport alternatives (defining system boundary), design the socio-technical system, define data and evidence, criteria formulation.
ii. Analysis: Criteria assessment, scoring, weighting, sensitivity analysis.
iii. Decision: Ranking of alternatives and determining the best overall transport option.

The Data and evidence for carrying out the MCA was based on publicly available literature including but not limited to,
a. Peer reviewed scientific papers, journals, books and student theses
b. Hyperloop related news articles, public and private company reports
c. Development plans and transport plans/reports at the regional, national (Dutch, German) and European level.
d. Dutch databases (Statistics Netherlands, 2020), European statistical databases (European Commission, 2020a) and other databases such as OECD (2020).

Wherever concrete data was not available, data available from similar geographic regions (preferably from EU & OECD countries) was used and suitable assumptions were made wherever required. Calculations and derivations were made on existing data using suitable assumptions and any new data measurements remained out of scope of this project except the data collected from 2 anonymous digital surveys for the weighting process in the sensitivity analysis.

3. Criteria Formulation

Given the aim, objectives and system boundaries, the socio-technical transport system for hyperloop, rail and aviation transport in Netherlands and Germany was defined after brainstorming about the elements such as the technical artefacts, actors and rules which were based on the concepts described in Geels (2004). The implication of formulating the socio-technical transport system in this project was to identify the rules/policies such as the local/national/EU development and transport policies. These policies would be later used to identify relevant objectives which in turn were used to formulate the assessment criteria. The socio-technical transport system was also used to identify the stakeholders which were used in the weighting process in the sensitivity analysis later on in the MCA process. The visual representation of the defined socio-technical transport system for hyperloop, rail and aviation is shown in Figure 5.

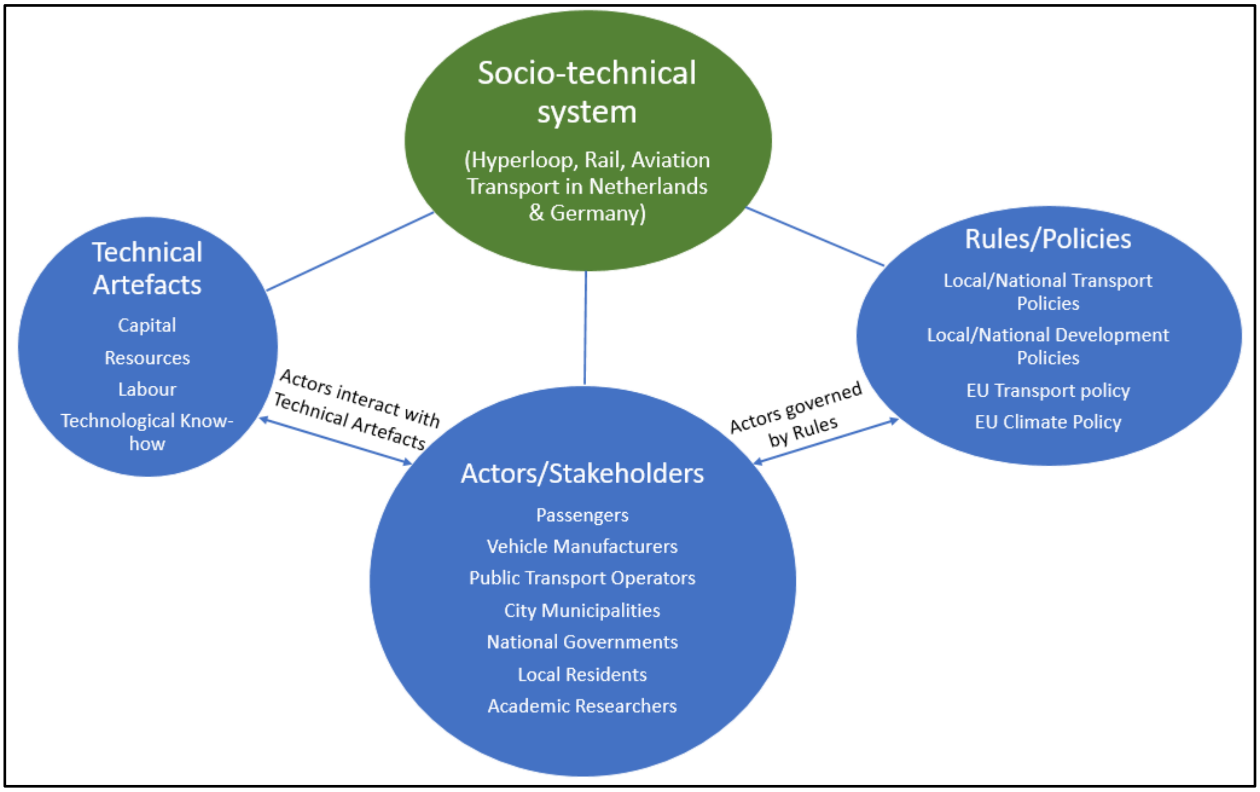

Figure 5: Socio-technical transport system for Hyperloop, Rail and Aviation in Netherlands and Germany based on the socio-technical system concepts described by Geels (2004).

The MCA framework defines the process followed for the identification and formulation of the criteria for assessment. The basis of the MCA framework was formed by the relevant objectives defined in regional/national/european general development and transport plans/reports as well as the UN SDG targets. These relevant objectives chosen from above regional/national/european general development and transport plans/reports were broadly classified into social, socio-economic and environmental objectives. Relevant UN SDG targets and indicators(United Nations, 2020a) were also identified and grouped together with similar objectives. This grouping of similar objectives and targets together formed a single criteria. A total of 6 criteria were thus formed and are described in Table 1.

Table 1: Objective Identification, Grouping and Formulation into Criteria.

Criteria formulated from the grouping together of similar relevant objectives and related UN SDG Indicators	**The regional/national/european general development and transport plans/reports from which the relevant objectives were identified are listed below**	**Related UN SDGs**
Social Criteria		
1.Safety (measured as number of accidents, other safety aspects)	A, B, C*	SDG 3, Target 3.6, Indicator 3.6.1(United Nations, 2020b)
2.Noise (measured as decibel (dB))	A*	
3.Travel time (measured as journey time between destinations)	A, B, C*	
Socio-Economic Criteria		
4.Connectivity (measured as affordability, equitable access, better airport connectivity)	A, B, C, D, E*	SDG 9, Target 9.1, Indicator 9.1.2(United Nations, 2020c)
Environmental Criteria		
5.Emissions (measured as direct CO_2 emissions per passenger per km)	A, B, C, D, E*	SDG 13, Target 13.2 (United Nations, 2020d)
6.Land-use (measured as land used in hectares)	A*	SDG 15, Target 15.3, Indicator 15.3.1(United Nations, 2020e)
*Note: Objective and Target details are mentioned in Appendix A. Each letter denotes a regional/national/european general development or transport plans/reports as listed below, *A. The 2030 Federal Transport Infrastructure Plan (Federal Ministry of Transport and Digital Infrastructure, 2016)*		

B. Public Transport in 2040: Outlines of a Vision for the Future (Ministry of Infrastructure and Water Management et al., 2019)
C. Goals of public transport policy (Government of the Netherlands, 2020b)
D. Transport 2050: Commission outlines ambitious plan to increase mobility and reduce emissions (European Commission, 2011)
E. Agenda voor een toekomstbestendige en evenwichtige metropool 2020-2024 (MRA Bureau, 2020)

The visual representation of the MCA framework used for identifying criteria is shown in Figure 6. The figure shows the derived criteria for each aspect of society, environment and the economy. The criteria "Connectivity" covered socio-economic objectives and hence is shown under both society and economy in the visual representation.

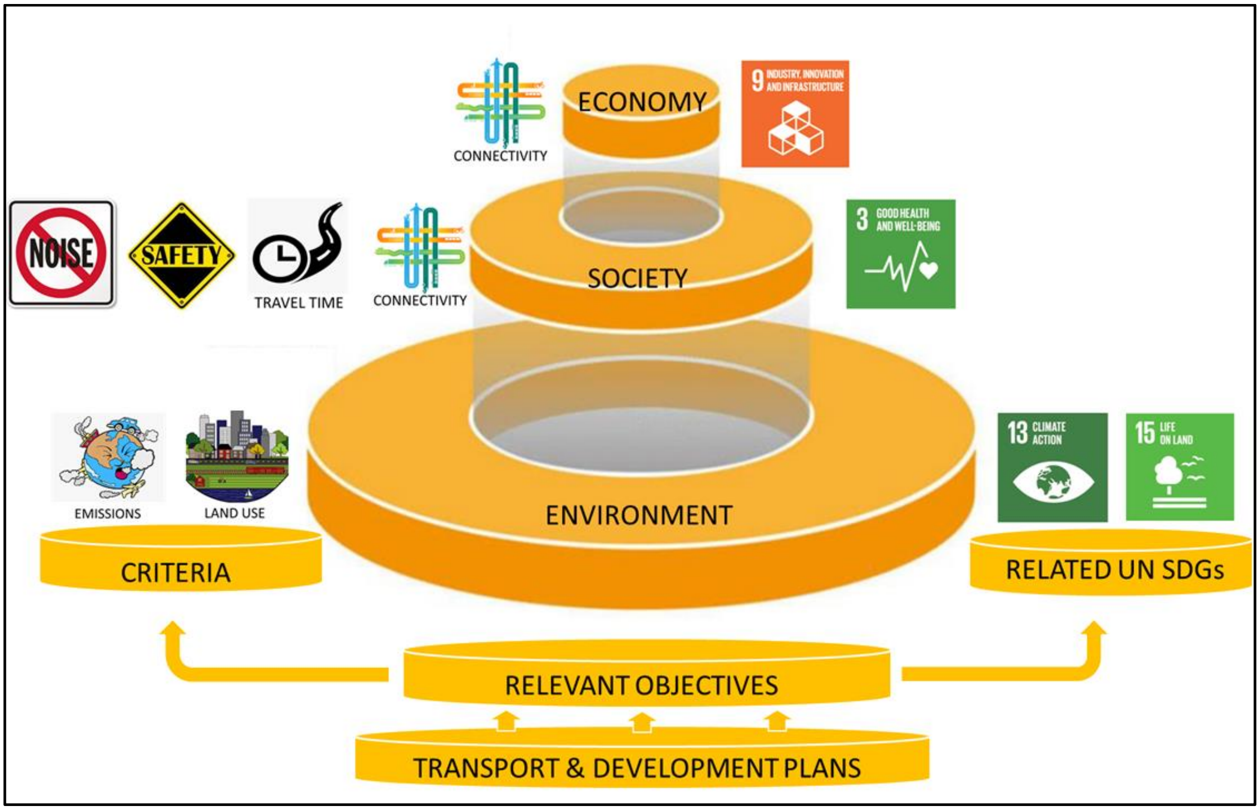

Figure 6: Visual representation of the MCA Framework (Process for identifying criteria)
(the visual representation was an adaptation of the image "*Humanity's development within the biosphere*" by Gordon (2018)).

4. Analysis

4.1 Criteria Assessment

Quantitative and qualitative data collected for each criteria was subdivided into various subcriteria. There were a total of 6 criteria and 22 underlying subcriteria formulated for comparison of the three alternatives. The assessment of these criteria for the 3 transport alternatives is presented in the criteria assessment Tables 2, 3, 4, 5, 6 and 7. This criteria assessment formed the basis for the scoring of the criteria in the next step of the MCA. The criteria assessment done in this study has several limitations which are elaborated in the Discussion section.

Table 2: Assessment of Safety Criteria for the three alternatives.

1. Safety		
Hyperloop	**Rail**	**Aviation**
Subcriteria: External Interaction accidents		
Fully enclosed system with no external interactions (Taylor, et al., 2016). Hence, accidents of external interaction accidents category were assumed to be 0.	There were 834.1, 119.9 and 18.7 Rail level crossing accidents* in the EU, Germany and Netherlands respectively (European Commision, 2020b). There were 1482.2, 193.1 and 4.4 Accidents to persons caused by rolling stock in motion* (Unauthorized persons on railway tracks) in the EU, Germany and Netherlands respectively (European Commision, 2020b).	There were 11.33, 1.75 and 0.667 Runway accidents** in the EU, Germany and Netherlands respectively (ICAO, 2020a).
*2006 - 2015 figures (European Commision, 2020b) annual average taken for a 10 year period. These types of accidents though higher in number are generally reducing with a few outliers for most number of years from 2006 to 2015. Efforts are being made to prevent such accidents e.g. The European Level Crossing Forum (ELCF) is a working group that brings together stakeholders for better management of rail crossings (UIC, 2020b). **2008 - 2019 figures (ICAO, 2020a) annual average taken for a 12 year period. These types of accidents although lower in number, several preventive measures are being proposed and implemented (EASA, 2019).		

Subcriteria: Human factors (accidents caused due to manual errors)		
As Hyperloop is a completely automated system (Taylor, et al., 2016), accidents caused due to manual error are assumed to be 0.	Typical human errors in rail operations are signal passing, train speed, signalling/dispatching (Dhillon, 2007). 3.6% of main causes of rail accidents in the EU were human factors (caused by railway staff or subcontractors) (2013-2018 figures) (UIC, 2019).	Between 2015 - 2019, LOC-I (Loss of control inflight) was the most common fatal accident (19 accidents, 780 deaths). Top primary contributing factor for accidents (39%) was flight crew errors (caused by manual handling/flight controls) (IATA, 2020).
Subcriteria: Automation (prevention of accidents through automation)		
Hyperloop is completely automated with no pilot or driver (Taylor, et al., 2016). Hence the accidents due to manual errors can be prevented. However, due to such a high level of automation and lesser chance of human intervention in case something goes wrong, rigorous and exhaustive testing will be required to ensure system safety. People will be willing to use the system only if Hyperloop has gone through rigorous testing and safety certifications.	Driver is required for trains with some automation available such as European Train Control System (ETCS) which continuously calculates a safe maximum speed for each train, signalling to the driver and the system takes control if permissible speed exceeded thus ensuring trains operate safely (UIC, 2020a). There is still some likelihood of manual error causing accidents.	For civilian aircraft, a pilot and copilot are required with advanced automation available to avoid collisions. There is less likelihood of mid-air collisions due to Airborne Collision Avoidance System (ACAS)/Traffic Collision Avoidance System (TCAS) and set operational procedures for flight crews and Air Traffic Control (ATC) (IATA, 2020). ILS (Instrument Landing system) is another automation aid for navigation which enables pilots for a precision approach and landing to a runway (approved by ICAO and used for over 40 years) (IATA, 2010). There is some likelihood of manual error causing accidents.
Subcriteria: Depressurization (Pa = Pascal, a unit of pressure)		
Hyperloop vacuum tube pressure is 100 Pa (Dudnikov, 2018) which is lower and potentially more dangerous as	No risk of depressurization as trains operate at ambient air pressure on ground level.	Aircraft operate at external pressure 19399 Pa (altitude of 12000m). In case of depressurization, oxygen masks

compared to aircraft external operating pressure. As per Musk (2013), in case of a small air leak inside the Hyperloop pod, the reserved air carried onboard can maintain air pressure. Such a system could function for 7.5 - 15 min (Dudnikov, 2018). In case of a serious incident, oxygen masks would be deployed similar to aircraft which help the passengers in breathing (Taylor, et al., 2016).		are deployed (running 10-15 min) helping passengers to breathe and also during this time, the pilots lower the aircraft to a safer altitude (3000m) and safer operating external pressure (making more oxygen available for passengers for breathing). (Dudnikov, 2018)
Subcriteria: Rapid pressurization of vacuum tube		
Sudden pressure increase due to leakage of ambient air from outside the tube would potentially cause a deceleration of 5 g, considered a safe figure (Schulz, et al., 2017).	No risk of rapid pressurization as vacuum tubes not used.	No risk of rapid pressurization as vacuum tubes not used.
Subcriteria: Medical emergency onboard		
The hyperloop pod finishes the remaining journey in a few mins (Musk, 2013;Taylor, et al., 2016) and medical services could be made available at the next station. Amsterdam-Frankfurt total journey time of 83 min with stations every 10 - 25 min apart (Prov. N-Holland & Hardt, 2020).	Medical services available at the next station. Amsterdam-Frankfurt journey with stations every 15 - 60 min apart (Deutsche Bahn, 2020). Trains also have the possibility to make an emergency stop anywhere on the track and road/air ambulances can be used for quick evacuation.	Aircraft completes its journey or makes an emergency landing at an alternate airport. Amsterdam - Frankfurt total travel time of 95 min (Lufthansa, 2020) or lesser time making an emergency landing at an alternate airport.
Subcriteria: Stopping Distance		
The stopping distance of a hyperloop pod is 4000m with	The stopping distance of ICE High speed train (ICE-	Aircraft while in the air can manoeuvre in the air space to

a deceleration of 1g, 30 sec headway between two hyperloop pods is feasible as per calculations by NASA. Additional mechanical braking system is available as redundancy (Taylor, et al., 2016).	V version) is 1,200 m at 200 kmph (Sands, 1992).	avoid obstacles and only need to stop after landing at the airport. The usual stopping distance on the runway is upto 2000m (for Airbus A319 which is one of the aircraft used on AMS - FRA route, the stopping distance ranges from 766m - 1139m) (Van Es et al., 2010)
Subcriteria: Technology readiness ***(TRL is the Technology Readiness Level (from Level 1 to Level 9) to denote the maturity level of a technology as defined by NASA) (NASA, 2012)		
Hyperloop is a new technology which is not yet commercially deployed. Further consideration is required to assess safety (Van Goeverden, et al., 2018). Such as the evacuation of people, emergency exits and stranded capsules (Taylor, et al., 2016). Hyperloop can be said to have achieved TRL 6 (System/subsystem model or prototype demonstration in a relevant environment)***	High speed rail is a proven commercially deployed technology in use with continuous incremental safety improvements. High Speed Rail can be said to have achieved the highest TRL 9 (Actual system proven through successful mission operations)***	Aviation is a proven commercially deployed technology in use with continuous incremental safety improvements. Aviation can be said to have achieved the highest TRL 9 (Actual system proven through successful mission operations)***

Table 3: Assessment of Noise Criteria for the three alternatives.

2. Noise		
Hyperloop	**Rail**	**Aviation**
Subcriteria: Local exposure		
The hyperloop hardly produces any external noise (Van Goeverden, et al., 2018) because the hyperloop pods are not in contact with the vacuum tube and hence there is no transfer of vibration. Also, noise from inside the pod will not be heard outside due to low pressure inside the	The local noise exposure of an observer at 25 m distance away from a passing HS train is in the range of 84 - 105 dBA (depending on speed variation) (Van Goeverden, et al., 2017). For the (ICE-V) train the local noise exposure is 79 - 102	The local noise exposure of aircraft at the airport is in the range of 46 - 92.5 dBA (Van Goeverden, et al., 2017).

tube. Noise could be generated from the vacuum pumps, but was assumed to be negligible by Wilkinson (2016) cited in Van Goeverden, et al. (2017). Noise could be generated from the swing created by the push of pressure against the vacuum tube's inner walls but it is likely to be < 50 dB. (Forschungsgesellschaft für Straßen und Verkehrswesen, 2015) cited in (Werner, et al., 2016).	dBA (speed range of 160 - 400 kmph) (Sands, 1993). Newer generations of this train run along AMS - FRA route so the actual noise exposure might be lower due to subsequent improvements in rail technology since the 1990s. In several places in Europe, sound barriers are employed on the tracks near residential areas for the reduction of noise pollution for the residents.	
Subcriteria: Population exposure *Lden is the EU indicator of a person's exposure over a year corresponding to the average noise level through the day, evening and night period (European Commission, 2020c).		
The hyperloop hardly produces any external noise thus affecting relatively close by population (Van Goeverden, et al., 2018) (relatively lesser population) because the hyperloop pods are not in contact with the vacuum tube and hence there is no transfer of vibration. Also, noise from inside the pod will not be heard outside due to low pressure inside the tube (Van Goeverden, et al., 2017). Due to all the above factors, the population exposed to the low noise levels (<50 dB) will be limited to the population in the close proximity of the Hyperloop tube. In case the Hyperloop is built alongside existing infrastructure like highways, the perceived noise from Hyperloop will be masked by the already noisy highway (e.g. road noise	It was estimated that almost 22 million people are exposed to rail traffic noise >55 dB Lden* (11 million in urban areas + 11 million outside urban areas) (EEA, 2020).	It was estimated that aircraft noise exposes almost 4 million people are exposed to air traffic noise >= 55 dB Lden* (3 million in urban areas + 1 million outside urban areas) (EEA, 2020).

exposure >55 dB Lden* for 82 million + 31 million people (EEA, 2020)).		

Table 4: Assessment of Travel time Criteria for the three alternatives.

3. Travel time		
Hyperloop	**Rail**	**Aviation**
Subcriteria: Amsterdam - Frankfurt (travel time over full route)		
83 min* (Prov. N-Holland & Hardt, 2020)	263 min** (Deutsche Bahn, 2020a)	215 min*** (Lufthansa, 2020 & KLM, 2020)
*Including 30 min access and egress time (Prov. N-Holland & Hardt, 2020). With an assumption that Hyperloop stations are located close to city centers similar to railway stations. **Including 30 min access and egress time which is assumed same as Hyperloop due to similarities in location and layout of stations. ***Including access and egress time of 145 min for air travel which is assumed to be significantly higher due to baggage check in, security checks and baggage claim. Amsterdam airport recommends passengers to check in 2 hours (120 min) before departure for travel within Europe (Schiphol, 2020) and might need 25 to 40 min for baggage collection(Royal Schiphol Group, 2020) if they have checked in baggage. Hence access and egress time assumed as 145 min (120+25min)).		
Subcriteria: Amsterdam - Utrecht (travel time between stations)		
35 min* (Prov. N-Holland & Hardt, 2020)	58 min** (Deutsche Bahn, 2020a)	No airport at Utrecht
Subcriteria: Amsterdam - Eindhoven (travel time between stations)		
44 min* (Prov. N-Holland & Hardt, 2020)	110 min** (by NS Intercity) (NS, 2020a). Not serviced by ICE High speed train.	No direct flights available (Skyscanner, 2020a)
Subcriteria: Amsterdam - Düsseldorf (travel time between stations)		
58 min* (Prov. N-Holland & Hardt, 2020)	160 min** (Deutsche Bahn, 2020a)	195 min*** (KLM, 2020)

Table 5: Assessment of Connectivity Criteria for the three alternatives.

4. Connectivity		
Hyperloop	**Rail**	**Aviation**
Subcriteria: Smaller airport attractiveness Eindhoven (EIN) & Düsseldorf (DUS)		
Increases*	Remains same**	Remains same**
*A study on potential hyperloop between San Francisco and Los Angeles showed increased attractiveness for smaller airports in the region such as Burbank and Long beach airports (Voltes-Dorta & Becker, 2018). Similarly the attractiveness of the relatively smaller airports of Eindhoven and Düsseldorf could increase(for connections from other smaller airports outside the region) as they come within (39 - 44 min) & (25 - 58 min) travel distance of the big hub airports of Amsterdam and Frankfurt respectively(reducing transfer time for onward international journeys). For example, a passenger travelling from a small airport in Europe which does not have direct connectivity to Amsterdam/Frankfurt, could take a cheap flight to Eindhoven/Düsseldorf and then take a quick Hyperloop journey for onward international connection via Amsterdam/Frankfurt. Due to the perceived increased attractiveness of smaller airports if Hyperloop was built, there could also be rebound effects of increased usage of aircraft and hence increased emissions from these airports for connections outside the region, but since the system boundary was the flights between these 4 airports such rebound effects were not considered. This limitation could be addressed in a future study with a wider system boundary. **With current level of operations. For example Eindhoven is a small airport with no direct flights available from Amsterdam or Frankfurt. Also, Eindhoven is not serviced by the high speed ICE train and it will take 110 min direct by NS Intercity (NS, 2020a) from Amsterdam and at least 297 min with one or more transfers (NS, 2020b) (rail time figures with 30 min access and egress time included).		
Subcriteria: Connected aviation hub Amsterdam (AMS), Frankfurt (FRA), Düsseldorf (DUS) & Eindhoven (EIN)		
Could potentially function as a larger aviation hub with airports connected by the Hyperloop system within 83 min travel time of each other.***	Continue to function as separate aviation hubs/airports connected by current rail systems within 263 min travel time of each other. Passengers still have the flexibility of choosing any of the airports but the connecting time is far higher than Hyperloop.	Continue to function as separate aviation hubs/airports connected by air within 215 min connecting travel time of each other. With the exception of Eindhoven which does not have any direct connecting flights to the other airports (Skyscanner, 2020a) hence making it infeasible to connect to other three airports

<table>
<tr><td></td><td></td><td>by air as rail travel will be quicker and cheaper.</td></tr>
<tr><td colspan="3">***Passengers get more flexibility to choose any of these airports for their travel into or from this region. This might increase the overall ticket price competition between these airports which could benefit the end consumers. Due to the increased flexibility and price competition, the combined competitiveness of this bigger connected aviation hub might increase and hence, together these airports with combined market capitalization of 174.387 million passengers could attract more passengers from other european aviation hubs such as Paris with 76.135 million passengers. Figures used were total airport passengers in million for the year 2019 (European Commission, 2020d). Total airport passengers in million for 2019 for Amsterdam (AMS): 70.436; Frankfurt (FRA): 71.690; Dusseldorf (DUS): 25.476; Eindhoven (EIN): 6.785 and Paris (CDG): 76.135 (European Commission, 2020d)
Also, any lack of capacity or increase in demand at the bigger airports such as Amsterdam and Frankfurt could be absorbed by adding more capacity at the other 2 smaller airports. The scope for growth for Eindhoven airport could be high as it is the smallest of the 4 airports by passenger numbers.</td></tr>
<tr><td colspan="3">Subcriteria: Affordability (Ticket prices from Amsterdam to Frankfurt) (pax = passenger)</td></tr>
<tr><td>Estimated ticket price for a 28 person Hyperloop pod was 171 €^ if entirely powered by Solar power. It was estimated to be 185 €^^ if grid power were to be used.</td><td>Actual ticket price: Upto 60 € (Sep 2020)
ICE train ticket price for second class direct train booked within one week of departure was considered (NS, 2020c).</td><td>Actual ticket price: 107 € - 158 € (Sep 2020)
Flight ticket price for economy class direct flight booked within one week of departure was considered (Skyscanner, 2020b).</td></tr>
<tr><td colspan="3">^Hyperloop estimated ticket price (if solar panels used) = 172 € (Cost per passenger per km x distance of track = 0.47 €/ pax km x 364 km = 171.08 € , rounded off to 171 €). A similar Hyperloop track distance with rail track distance was assumed between Amsterdam and Frankfurt (364 km) (Railcc, 2020). 0,47 €/ pax km was the cost estimated by Van Goeverden, et al., (2017) in the case of 50% solid soil, 40% weak soil, and 10% tunnel. 180 services per day per direction, 28 seats per capsule, 15 operating hours per day per capsule, with a station spacing of 500 km, a high network connectivity, and a load factor of 80%. Assuming that the energy from solar panels mounted on top of the tube exceeds consumption, hence operating energy costs were assumed to be 0) (Van Goeverden, et al., 2017).
^^Hyperloop estimated ticket price (if grid power used) = 185 € (Ticket price without energy costs + energy cost purchased from the grid = 171 € + (0.227 KWh/ pax km x 0.1538 € / KWh x 364 km) = 172 € + 12.70 € = 184.70 €, rounded off to 185 €). A similar Hyperloop track distance with rail track distance was assumed between Amsterdam and Frankfurt (364 km)(Railcc, 2020). Average energy consumption 165 Wh/ pax km (56 seater pod) and 227 Wh/ pax km (28 seater pod) (Janić, 2020). 28 seater hyperloop capacity pod figures were chosen for comparability. Values ranging from 100 to 500 km station spacing distance were available out of which the value of 100km was chosen as it was the lowest value available closer to the actual ground distances between stations (Amsterdam - Frankfurt route will have station distances at</td></tr>
</table>

approximately 44km, 91km, 116km, 228km as calculated using Google Maps). 2019 figures for the electricity costs for non household consumers for Netherlands was 0.1087 €/KWh and for Germany was 0.1989 €/KWh (European Commission, 2020e). The average electricity cost (0.1538 €/KWh) of both countries was used in calculations. The numeric values from the Graph were derived wherever necessary using the WebPlotDigitizer tool created by Rohatgi (2010).		
Subcriteria: Reliability		
Can operate in all weather conditions(rain and snow) (Taylor, et al., 2016) as it is a fully enclosed system. Can possibly serve as a backup system for aviation/rail in case of severe weather events. However, in the event of maintenance on a tube in one direction, that full tube will need to be closed as a single tube allows only unidirectional travel.	High speed trains are affected by ice and snow events, but far more resilient than aviation (Taylor, et al., 2016). Can be used as a backup system for aviation in case of severe weather events and for hyperloop in case of maintenance. In the event of maintenance on the tracks, sections of the track will need to be closed and single track can be used for train traffic in both directions with passing siding track sections.	Aviation is highly affected by weather events (Taylor, et al., 2016). For example the ash cloud from Icelandic volcano in 2010 which led to a lot of flights being cancelled (EASA, 2020).
Subcriteria: Equitable access		
Hyperloop might be accessible to only premium paying passengers willing to pay the estimated relatively high ticket prices for travel time savings. (Taylor, et al., 2016; Van Goeverden et al., 2017; Nikitas et al., 2017) Companies such as Hardt and Hyperloop One aim to provide passenger comfort comparable to airplanes. It is expected that passengers will have to be seated and wearing seatbelts in case of emergency braking (Arup et al., 2017). This might force the reduced mobility passengers to store the	Due to the relatively low ticket price, high speed ICE trains are accessible to a wide range of passengers. There are 2 to 4 wheelchair spaces in every ICE International train (2nd class) and there are handicap washroom/toilet facilities. Next to each wheelchair space there is a reserved seat for the accompanying passenger (NS, 2020d). Battery operated mobility scooters are also allowed with limited options and reduced mobility or visually impaired persons may take one accompanying passenger or	Due to the relatively high ticket price, air travel is accessible only to a limited range of passengers. There are certain accessibility issues aboard aircraft for reduced mobility persons for e.g. battery operated wheelchair cannot be brought in the cabin and needs to be stored in the luggage compartment and even the foldable wheelchair/crutches/canes/walkers needs to be stowed under the seat or in overhead compartment during the flight forcing the passenger to use the airplane seat with seatbelt for safety reasons (DOT,

wheelchair and instead use the hyperloop seats with seat belts for safety reasons similar to airplanes.	assistance dog with them free of charge (NS, 2020e).	2017). Regulations and rights of reduced mobility aviation passengers (European Commission, 2012;European Union, 2020) are in place but there are several reports of reduced mobility passengers facing difficulties (Ryan, 2018;Schulson, 2019). Also, wheelchair accessible lavatories may or may not be available on single aisle aircraft (WheelchairTravel.org, 2020) such as on the type of aircraft used on the Amsterdam-Frankfurt route.

Table 6: Assessment of Emissions Criteria for the three alternatives.

5. Emissions		
Hyperloop	**Rail**	**Aviation**
Subcriteria: Estimated CO_2 emissions (direct emissions during operation) (pax = passenger)		
Estimated CO_2 emissions for 56 person Hyperloop pod are 31 g CO_2 / pax km* and for 28 person pod are 63 g CO_2 / pax km* (Janić, 2020).	Estimated CO_2 emissions for 430 person ICE 3 high speed train are 47 g CO_2 / pax km* (Janić, 2020).	Estimated CO_2 emissions for 189 person Boeing 737/8 are 99 g CO_2 / pax km* (Janić, 2020). For 76-220 person Airbus 319/320/321/32A or Boeing 737 or Embraer E75/E90 are 186 g CO_2 / pax km** (ICAO, 2020b).
*Estimated CO_2 emissions for 500km journey distance (Janić, 2020). The CO_2 emissions were estimated only for direct emissions during operation. The emissions from other lifecycle stages such as during the construction phase were not included. Out of the two datasets available for 500km and 1000km journey distance emission figures, 500km was chosen as it was closer to Amsterdam and Frankfurt rail distance (364 km) (Railcc, 2020) and air distance (367 km) (ICAO, 2020b). **68.3 kg CO_2 / pax km for flight from Amsterdam to Frankfurt for 367 km rated flying distance (ICAO, 2020b). Conversion to g CO_2 / pax km (68.3 kg / pax = 68.3 x 1000g / 367 km = 186.1 g/ pax km, rounded off to 186 g / pax km). The emissions were estimated only for		

direct emissions during operation. The emissions from other lifecycle stages such as during the construction phase were not included. The high altitude effects of aircraft emissions such as radiative forcing were not considered.

Table 7: Assessment of Land-use Criteria for the three alternatives.

6. **Land-use**		
Hyperloop	**Rail**	**Aviation**
Subcriteria: Estimated direct land-use (for line infrastructure) (ha = hectare)		
Estimated direct land used for Hyperloop vacuum tube and pillars infrastructure between Amsterdam and Frankfurt excluding the hyperloop stations is 364 ha*.	Estimated direct land used for Railway line infrastructure between Amsterdam and Frankfurt excluding the railway stations is 1278 ha**.	Estimated direct land used for Aviation runway infrastructure for the 4 airports of Amsterdam, Frankfurt, Düsseldorf and Eindhoven excluding the Airport buildings is 207 ha***.
*Estimated direct land used by the line infrastructure is upto 1.0 ha per km of Hyperloop line infrastructure (Van Goeverden, et al., 2017). This is the estimated direct land used by the Hyperloop vacuum tube and pillars and does not include the land used by Hyperloop stations. The estimated data is for two vacuum tubes running side by side and carrying pods in each direction and both the tubes are supported by a single row of pillars on the ground. Amsterdam and Frankfurt rail distance is 364 km (Railcc, 2020). Assuming the total length of the line infrastructure required for Hyperloop is similar to Rail, the estimated direct land use for line infrastructure = 1.0 ha/km x 364 km = 364 ha. **Estimated direct land used by the line infrastructure is upto 3.5 ha per km of Rail line infrastructure (Van Goeverden, et al., 2017). This is the direct land used by the railway line infrastructure and does not include the land used by railway stations. It is assumed that the railway line supports travel in both directions either through the use of a bi-directional railway line or a double track railway line. Only one such line was considered in the calculation for the sake of simplicity but there might be several parallel lines along Route 3. Amsterdam and Frankfurt rail distance is 364 km (Railcc, 2020). Hence, the estimated direct land use for line infrastructure = 3.5 ha/km x 364 km = 1277.5 ha which is rounded off to 1278 ha. ***Estimated direct land used by the line infrastructure is upto 15 ha per km of Aviation line infrastructure (Van Goeverden, et al., 2017). This is the estimated direct land used by the runway infrastructure and does not include the land used by airport buildings. For the four airports considered, Amsterdam had 5 runways, Frankfurt had 4, Düsseldorf had 2 and Eindhoven had 1. These airports service a large European as well as international region. However, the system boundary in this study for aviation was the flights operating between the four airports. Hence, it was assumed that a single runway per airport would be sufficient to service only the flights between these 4 airports. Only one runway of the highest length per airport was chosen to calculate the direct land use. To estimate the direct land used by line infrastructure, the total		

length of the chosen 4 runways of the four airports of Amsterdam, Frankfurt, Düsseldorf and Eindhoven was multiplied by the estimated direct land used per km of line infrastructure. Chosen runway with highest length at Amsterdam = 3800 m = 3.8 km (SkyVector, 2020a). Chosen runway with highest length at Frankfurt = 4000 m = 4 km (SkyVector, 2020b). Chosen runway with highest length at Düsseldorf = 3000 m = 3 km (SkyVector, 2020c). Chosen runway with highest length at Eindhoven = 3000 m = 3 km (SkyVector, 2020d). Total length of runways = 3.8 + 4 + 3 + 3 = 13.8 km. Hence, the total estimated direct land used for line infrastructure = 15 ha / km x 13.8 km = 207 ha.		
Subcriteria: Stations/Airport direct land-use		
The Hyperloop stations will most likely be either elevated stations or underground and will require less space on ground as compared to conventional railway stations and airports and will be similar to elevated metro stations (Janberg, 2020) in cities around the world. Hyperloop stations will occupy less space than average rail stations as per the concept hyperloop station designed by Roux (2013).	Conventional Rail stations are far lesser in size than airports (Van Goeverden, et al., 2017) and require even lesser land for the stations which are elevated. All the rail stations on Route 3 are on the ground level.	Airports need more space as compared to the rail and hyperloop stations (Van Goeverden, et al., 2017).

4.2 Scoring

The impact of each transport alternative for each subcriteria was evaluated according to five possible grades and converted into scores (in brackets): very positive (5), positive (4), neutral (3), negative (2), and highly negative(1). This scoring grade and methodology was an adaptation of the scoring used in the multicriteria analysis by Martínez-Díaz, Soriguera & Pérez (2018).

The given scores result from the expert consideration and relative comparison of the quantitative and qualitative data collected for each sub criteria for each alternative(see criteria assessment table X). Before scoring the subcriteria, the criteria were classified into two groups as below;
1. Criteria with possible adverse impacts (Safety, Noise, Emissions, Land-use).
2. Criteria with possible favourable impacts (Travel time, Connectivity).

For each subcriteria under the first type of criteria, the relatively worst transport alternative was identified and a score was set for that alternative. The scores for the other two alternatives were then set relative to the worst. Reference scoring values used as guidance for the first type of Criteria were; 1 - Extremely high risk of adverse impact, 3 - Moderate risk of adverse impact, 5 - Miniscule or zero risk of adverse impact.

For each subcriteria under the second type of criteria, the relatively best alternative was identified and the score was set for that alternative. The scores for the other two alternatives were then set relative to the best. Reference scoring values used as guidance for the second type of Criteria were; 5 - Highly favourable impact, 3 - Moderately favourable impact, 1 - No favourable impact.

Subcriteria scoring is explained for a few examples below,
Example(i): For the subcriteria with comparable numeric values such as for Safety - Stopping Distance, Noise - Local Exposure and Population exposure, Estimated GHG emissions, Estimated direct land use and Travel time, the scoring was straightforward as the alternative with the highest numeric value received the lowest relative score and vice versa.

Example(ii): For the type 1 subcriteria, Rapid pressurization of vacuum tube, there is a risk of this happening with the Hyperloop vacuum tube with estimation of 5g deceleration for the passengers and in such an event which was considered a safe figure(Schulz, et al., 2017). Still a risk of injury cannot be ruled out. Also, since this is a new technology not yet commercially deployed, there remain some safety uncertainties. Also, since rail and aviation do not use vacuum tubes at all, Hyperloop was determined to be the worst alternative for this subcriteria and scored as 3. However, for rail and aviation this risk is not existent as vacuum tubes are not used hence both were scored as 5 relative to Hyperloop. The Unweighted scoring for each subcriteria is shown in Table 8.

Table 8: Unweighted criteria scoring per alternative.

Criteria	Subcriteria	Unweighted Criteria Scores		
		Hyperloop	Rail	Aviation
Safety	External Interaction accidents	5	3	4
	Human factors	5	4	3
	Automation	5	4	4
	Depressurization	2	5	3
	Rapid pressurization of vacuum tube	3	5	5
	Medical emergency onboard	4	5	3
	Stopping Distance	2	4	3
	Technology readiness	2	4	4
Noise	Local exposure	4	2	2
	Population exposure	4	1	2
Travel time	Amsterdam - Frankfurt (travel time over full route)	5	3	4
	Amsterdam - Utrecht	4	3	2
	Amsterdam - Eindhoven	5	3	2
	Amsterdam - Düsseldorf	5	4	3
Connectivity	Smaller airport attractiveness	4	3	3
	Connected aviation hub	4	3	3

	Affordability	2	5	3
	Equitable access	2	5	3
	Reliability	4	5	3
Emissions	Estimated GHG emissions	3	4	1
Land-use	Estimated direct land use	3	2	4
	Stations/Airport land use	3	3	2

Since there are different numbers of sub-criteria for each criteria, to ensure the equal consideration of every criteria, an average score of all subcriteria for each criteria was calculated and that score was used in the weighting process. These average scores per criteria were as shown in Table 9.

Table 9: Unweighted Average scores per criteria per alternative.

Average scores per Criteria	**Hyperloop**	**Rail**	**Aviation**
Safety	3.5	4.25	3.625
Noise	4	1.5	2
Travel time	4.75	3.25	2.75
Connectivity	3.2	4.2	3
Emissions	3	4	1
Land-use	3	2.5	3
Unweighted Total score* (Max score 30)	**Hyperloop**	**Rail**	**Aviation**
	21.45	19.7	15.375
*Unweighted total score is the sum of average scores per criteria for each alternative. The higher the score the better the alternative. The maximum possible score was 30 points.			

Hyperloop scored the highest closely followed by Rail, and Aviation had the lowest relative score. The same scores grouped into 3 criteria groups were as shown in Table 10.

Table 10: Unweighted Criteria Group Scores per alternative.

Criteria group scores*	**Hyperloop**	**Rail**	**Aviation**
Social (Safety, Noise, Travel time)(Max Score 15)	12.25	9	8.375
Socio-economic (Connectivity)(Max score 5)	3.2	4.2	3
Environmental (Emissions, Land-use)(Max score 10)	6	6.5	4
*Scores shown as sum of criteria wise average scores for each criteria grouping (social, socio-economic and environmental). The higher the score the better the alternative.			

4.3 Weighting

Three mock stakeholder profiles were chosen from the defined socio-technical system with different assumed values and different weights were assigned to the criteria for each profile. The concept of using these stakeholder profiles for weighting was based on the stakeholder profiles defined and used in the MCDA carried out by Ekener et al. (2018) and was adapted to the current transport problem. The three mock stakeholder profiles chosen were, 1. Passengers; 2. City Municipalities; 3. Local Residents.

4.3.1 Stakeholder Weighting for Passengers

For the determination of weights for the stakeholder profile of Passengers, an online survey was conducted with 307 anonymous individual participants (1st, 2nd and 3rd level social and work contacts of the author of varied demography resident in Europe, U.S.A and India) who were asked to rank the 6 transport criteria based on their priority (what they as a passenger perceived as most important for a travel distance of approximately 400km using rail/aviation/hyperloop). The free online tool Mentimeter (Mentimeter, 2020a) was used to conduct the survey with the weblink to the survey being shared through the social platform WhatsApp. Weights ranging from 1.5 to 1.0 with decreasing steps of 0.1 were applied to the 6 criteria from the highest ranked criteria to the lowest. The result of the survey and the applied weights is shown in Figure 7.

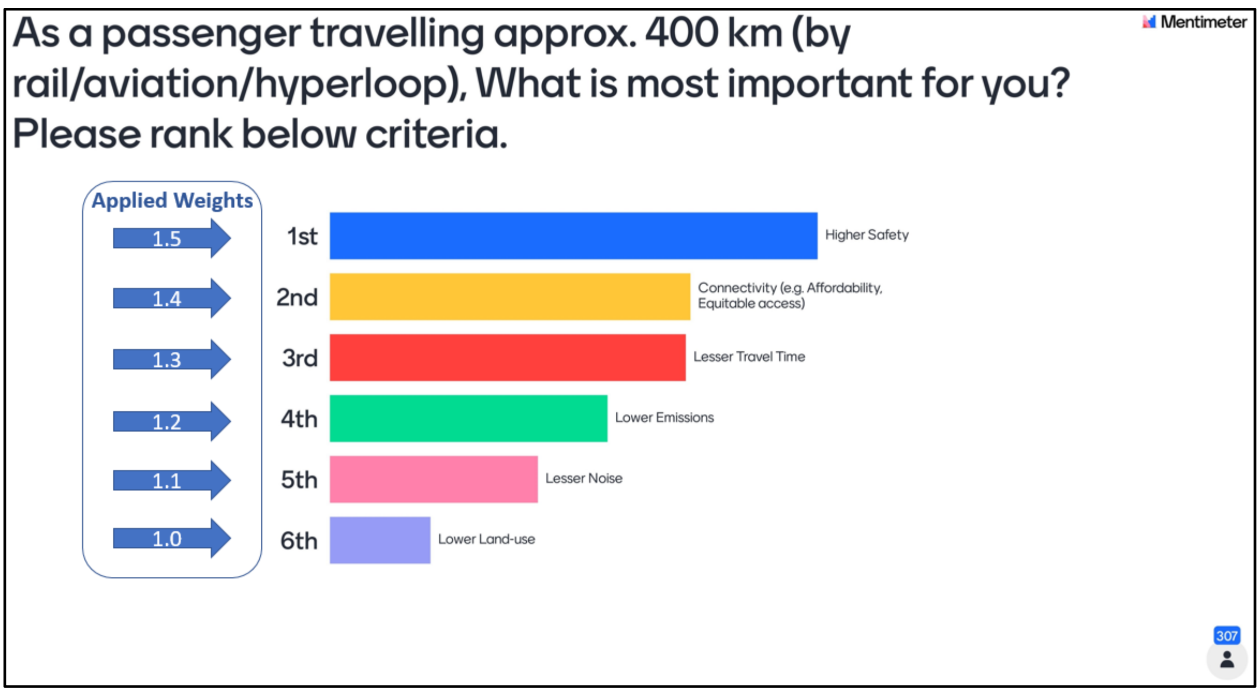

Figure 7. Deriving the priority of criteria for the stakeholder profile of Passengers using an online survey tool by Mentimeter (2020a).

4.3.2 Stakeholder Weighting for City Municipality

For the determination of weights for the stakeholder profile of City Municipality, published studies and city policies (for both Netherlands and Germany) showing the prioritized transport objectives were scarce. Traffic safety was listed as the heart of every measure of the transport policy for Amsterdam and a few keywords such as “safe”, “liveable city”, “accessible public spaces” were emphasized upon in the policy. The transport priorities in Germany have been changing (close links to the political majority) and recently the focus has been to increase the competitiveness and completion of specific projects (Fichert, 2017). Such prioritized transport projects were on the basis of achieving “network significance”, “value for money” and “environmental impact” (Federal Ministry of Transport and Digital Infrastructure, 2016).

Considering the above factors as pointers, certain assumptions were made to find out the priority for the city municipality through a brainstorming session. It is expected that any city municipality would want to increase connectivity to and from the city as better connectivity is generally considered as a prerequisite to increased economic prosperity. Good connectivity and the derived economic prosperity due to agglomeration benefits will lead to the increased attractiveness of the city and the willingness of people to move into such a city. Any city municipality is assumed to have a top priority to increase this, however, it would not want to increase this at the cost of safety of its citizens and the commuters travelling through its geographical boundaries. Hence, safety would be the first priority for the city municipality and connectivity would be second. Land being a key resource, the city municipality would want to allocate as little land as possible for the transport project as it needs land for constructing and expanding public utilities such as roads, hospitals, parks, town centres, police and fire stations etc. It would also want to restrict the noise pollution and GHG emissions from transport projects for its residents. Since noise pollution has immediate and direct local effects and the emissions from electricity usage by Hyperloop or Rail and the emissions from Aircraft have effects more on the global level (except in the case of location of airport near to the city, but in that case as well noise pollution has a much higher adverse local impact than the local emissions)

Noise pollution has immediate and direct local effects. On the other hand, emissions from electricity usage by hyperloop or rail and the emissions from aircraft have effects more on a global level. An exception to this is when the airport is near the city. Even in such a case, noise pollution has a much higher adverse local impact than emissions from taking off and landing aircraft. Hence noise is given a higher priority than emissions in this case. Reducing travel time to and from the city to other destinations becomes the least prioritized as it has the least adverse impacts relative to the other criteria. Weights ranging from 1.5 to 1.0 with decreasing steps of 0.1 were applied to the 6 criteria from the highest ranked criteria to the lowest as shown in Table 11.

Table 11: Application of Criteria Weights for the Stakeholder - City Municipality.

Criteria	Criteria Ranking	Applied Weights for City Municipality Stakeholder Profile
Safety	1	1.5
Connectivity	2	1.4
Land-use	3	1.3
Noise	4	1.2
Emissions	5	1.1
Travel time	6	1.0

4.3.3 Stakeholder Weighting for Local Residents

For the determination of weights for the stakeholder profile of Local Residents, an online survey was conducted with 18 anonymous individual participants (first and second level social and work contacts of the author of varied demography resident in Netherlands or Germany) who were asked to rank the 6 transport criteria based on their priority (what they as a resident perceived as most important if rail/aviation/hyperloop was built in their region). The free online tool Mentimeter (Mentimeter, 2020b) was used to conduct the survey with the weblink to the survey being shared through social platforms such as LinkedIn and WhatsApp. Weights ranging from 1.5 to 1.0 with decreasing steps of 0.1 were applied to the 6 criteria from the highest ranked criteria to the lowest. The result of the survey and the applied weights is shown in Figure 8.

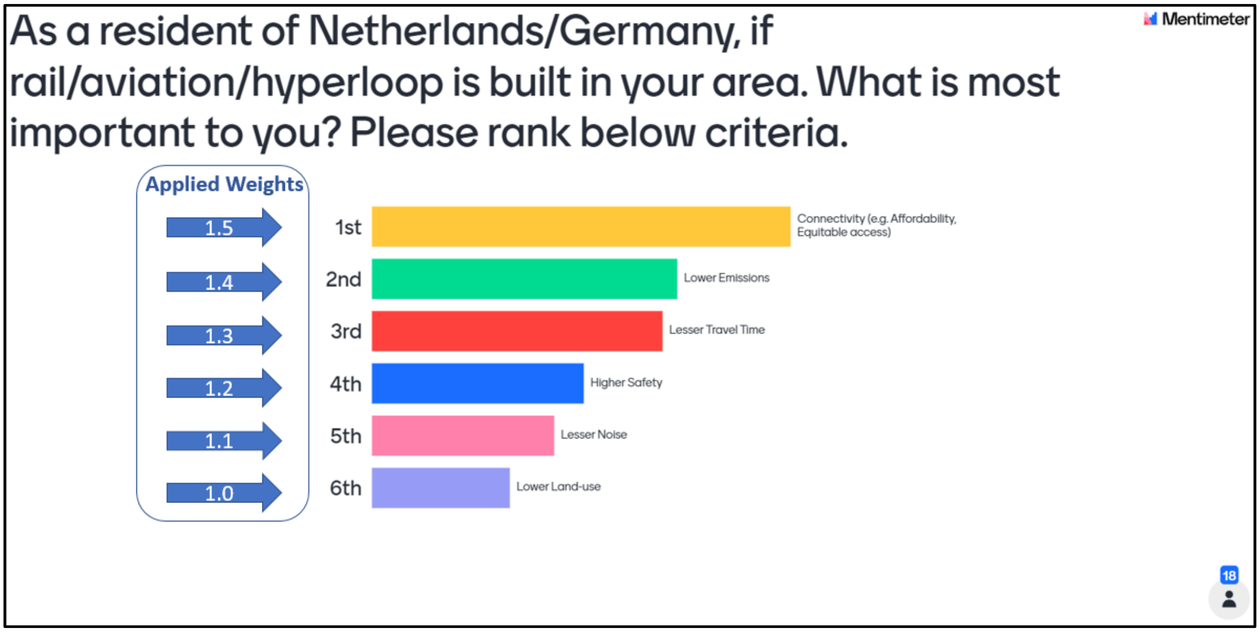

Figure 8: Deriving the priority of criteria for the stakeholder profile of Local Residents using an online survey tool by Mentimeter (2020b).

There were some notable differences in the criteria ranking survey result between passengers and local residents. While passengers ranked safety as highest and connectivity as 2nd highest, local residents ranked connectivity as the highest, emissions as 2nd highest while safety was ranked far lower at 4th. Travel time was ranked equally by both passengers and local residents alike. Noise and land-use were also ranked the same by both passengers and local residents as 5th and 6th respectively.

To the author's best knowledge such a digital survey was not conducted before for a transport related MCA study, but a similar survey was conducted (albeit more detailed with demographic data collection on a larger scale) for the Spårväg Syd (South Tramway in Stockholm) (Stockholms Läns Landsting, 2015). Good connectivity and equitable access were the common wishes of people participating in both the surveys. While more percentage of respondents cared about noise in the Stockholm survey, noise was ranked 5th for both Passengers as well as Local Resident surveys in this project. While a third of the Stockholm survey respondents thought the environment was the most important, emissions criteria was ranked 2nd in the Local Residents survey and 4th in the Passengers survey in this project. The final weights applied to each criteria for different stakeholders is shown in Table 12. These weights were applied to the criteria scores and a sensitivity analysis was conducted.

Table 12: Final Stakeholder Weighting Table.

Criteria	Applied Weights - Passengers	Applied Weights - City Municipality	Applied Weights - Local Residents
Safety	1.5	1.5	1.2
Noise	1.1	1.2	1.1
Connectivity	1.4	1.4	1.5
Travel time	1.3	1.0	1.3
Emissions	1.2	1.1	1.4
Land-use	1.0	1.3	1.0

4.4 Sensitivity Analysis

The weighted sum (or simple additive weighting) method was chosen for applying the weights because it was widely used (Triantaphyllou, 2000), simple in nature (Wątróbski et al., 2019) and was also used in a similar transport MCA study by Janic (2018). There was good availability of free software tools to implement this method and the result from the software tool was also easy to cross verify using manual calculations. Thus it was deemed suitable considering the time and resource limitations of this project. If there are p alternatives and q criteria then the best alternative is the one which returns the maximum value from the below equation. For i = 1,2,3...p and j = 1,2,3...q where a_{ij} is the score of the ith alternative for the jth criterion and w_j is the weight applied to the jth criterion. The total score will be the sum of products (Triantaphyllou, 2000; Mateo, 2012) (in this case p = 3 alternatives and j = 6 criteria and w ranging from 1.0 to 1.5).

$$Weighted\ Sum = \sum_{i}^{j} a_{ij} w_j \quad (Triantaphyllou, 2000; Mateo, 2012)$$

Based on the unweighted criteria scores and the derived criteria weights for each of the three stakeholder profiles, a simple weighted sum was calculated using the software tool Diviz Decision Deck (Decision Deck Consortium, 2018) for each set of weights of the three stakeholder profiles. The weighted sum model used can be seen in Figure 9.

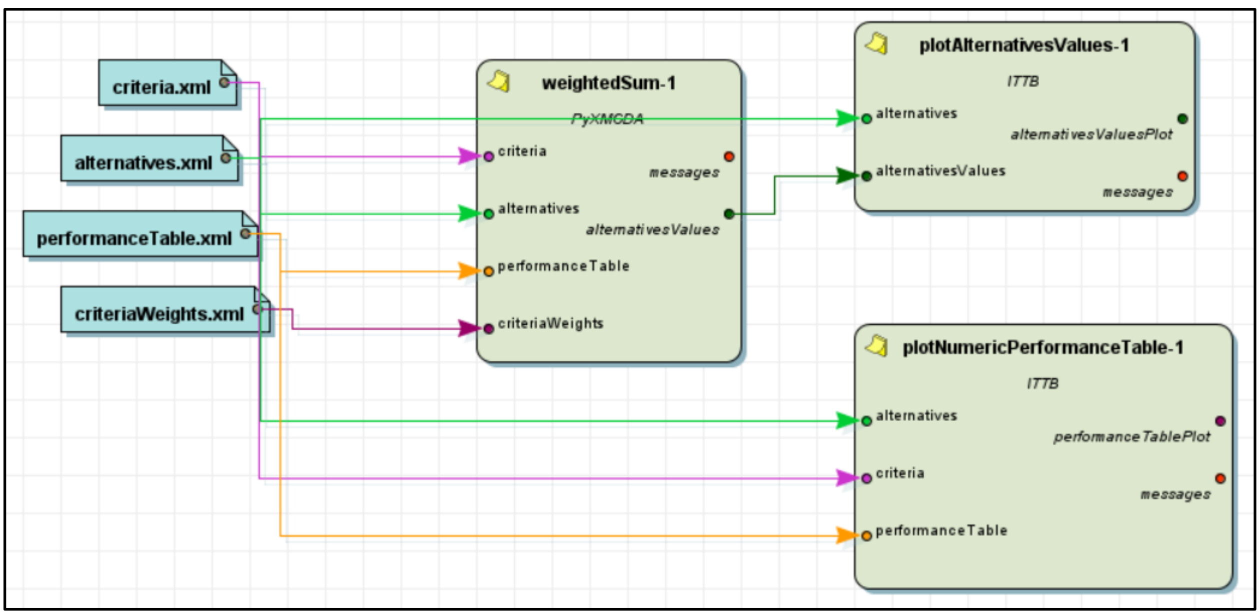

Figure 9: The weighted sum model used to apply different stakeholder weights to the MCA study using the software tool Diviz Decision Deck (Decision Deck Consortium, 2018).

The subcriteria, alternatives and the unweighted scoring for each subcriteria for each alternative were defined in xml files criteria.xml, alternatives.xml and performanceTable.xml respectively. The criteria weights for each stakeholder profile were input in the criteriaWeights.xml file. The program was iterated three times with a new criteriaWeights.xml for each stakeholder to calculate the weighted sum result for each stakeholder. After applying the different weights and calculation of the simple weighted sum, the weighted total scores were as shown in Table 13.

Table 13: Weighted Total Scores for each Stakeholder for each Alternative.

Weighted Total Scores	**Hyperloop**	**Rail**	**Aviation**
Weighted (Passengers) (Max score 37.5)	26.905	25.43	19.6125
Weighted (City Municipality) (Max score 37.5)	26.48	24.955	19.7875
Weighted (Local Residents) (Max score 37.5)	26.775	25.375	19.025

These weighted scores were normalized to a common scale for comparison with the unweighted scores and group criteria scores which are elaborated in the results section. The relation between the alternatives Hyperloop and Rail got slightly closer after weighting for different stakeholders. All the weighted scores for Hyperloop reduced slightly except the Passenger weighted score which increased slightly. All the weighted scores for Rail increased slightly compared to unweighted scores. The scores for the Aviation alternative also increased slightly after weighting except for Local Residents weighted score which decreased slightly. But these scores remained significantly lower than those for Hyperloop and Rail.

5. Results

After normalization of the unweighted total scores, the criteria group scores and the weighted total scores, the resultant scores were as shown in Table 14 and Table 15.

Table 14: Normalized Criteria Group Scores per Alternative.

Normalized Criteria Group Scores*	Hyperloop	Rail	Aviation
Social (Safety, Noise, Travel time)	81.67	60	55.83
Socio-economic (Connectivity)	64	84	60
Environmental (Emissions, Land-use)	60	65	40
*Scores were normalized to a scale with maximum possible score out of 100 and rounded off to two decimal places. Higher the score the better the alternative.			

Table 15: Unweighted and Weighted Normalized Total Scores per Alternative.

Normalized Total Scores*	Hyperloop	Rail	Aviation
Unweighted	71.5	65.67	51.25
Weighted (Passengers)	71.75	67.81	52.3
Weighted (City Municipality)	70.61	66.55	52.77
Weighted (Local Residents)	71.4	67.67	50.73
*Scores were normalized to a scale with maximum possible score out of 100 and rounded off to two decimal places. Higher the score the better the alternative.			

The resultant ranking of alternatives derived from the different scores is as shown in Table 16.

Table 16: The Overall and Grouped Criteria Ranking of Alternatives.

Ranking of Alternatives	Overall Ranking	Social Criteria	Socio-economic Criteria	Environmental Criteria
Rank 1	Hyperloop	Hyperloop	Rail	Rail
Rank 2	Rail	Rail	Hyperloop	Hyperloop
Rank 3	Aviation	Aviation	Aviation	Aviation

The unweighted as well as different weighted scores all showed that Hyperloop was relatively the best alternative, closely followed by Rail, and Aviation was the worst alternative. Hyperloop scored the best for Social criteria, significantly higher than Rail and Aviation. However, Rail scored the best for Socio-economic criteria, significantly higher than both Hyperloop and Aviation. Rail scored the best from the Environmental criteria as well, slightly higher than Hyperloop while Aviation scored the lowest, significantly lower than the other alternatives.

6. Discussion and Conclusion

The results of this study were dependent on the methodological choices made in this study. Key methodological choices that could have potentially influenced the results were the choice of criteria, subcriteria and the choice of weights during the weighting process. While the criteria were chosen from local/national/EU objectives and targets, the chosen subcriteria were dependent on the availability of comparable quantitative and qualitative data for the transport alternatives. This was especially true for Hyperloop as it was not yet commercially deployed. The additionally identified criteria “Innovation” was excluded from this project because the objectives were too wide in nature and there was lack of comparable qualitative and quantitative data for the alternatives. If “Innovation” criteria were to be included, it could have possibly resulted in higher scores for the Hyperloop alternative. “Decongestion of roads” was also identified as a criteria but excluded because the system boundary did not include “Road” as an alternative and the type of transport was restricted to people transport. If it were to be included as a criteria, there would be a need to expand the system boundaries of the study to include freight transport, since much of the freight transport happens by road today. This could increase the complexity of the study.

The choice of weights could also have had an influence on the results of this study. From the local/national/EU transport plans and policies, none of the individual criteria stood out as far more important than the other criteria. Due to this, the weighting scale with a smaller range of 1.0 to 1.5 and with short steps of 0.1 was chosen. For the highest stakeholder weighted criteria such as safety and connectivity, the unweighted scores for them were highest for the Rail alternative. Thus, if a higher range of weighing scale were to be chosen, the weighted total scores for Rail could be more closer to or possibly even higher than the Hyperloop alternative.

A notable result from the rankings was that aviation was ranked last for the overall ranking as well as from social, socio-economic and environmental group criteria rankings. This was mainly due to the significantly lesser scores for aviation for the environmental criteria due to relatively poor environmental performance. The criteria group scores for aviation were lowest but closer to rail for the social criteria group and closer to hyperloop for the socio-economic criteria group. This could be due to the short distance between the cities on the ends of the route. If longer routes were to be considered, aviation might have scored better than it did in the socio-economic criteria group due to the travel time savings for aviation over a long route. Aviation was the last ranked alternative with poor environmental performance and hence there is good potential for Hyperloop to be used by the environmentally conscious customer who might be willing to pay a slightly higher price than a flight as an alternative for short haul flights between cities in the region.

While Hyperloop has the potential to replace short haul flights and could act as a good complement to the rail and aviation network in the region, since it is a new technology there are several uncertainties. There is the added uncertainty about the governments’/private investors’ willingness to invest in the high initial cost of Hyperloop construction and its widespread acceptance due to the high estimated ticket prices. These estimated high ticket prices of Hyperloop present the risk of it being limited to only premium paying passengers and hence rail might continue to remain the most affordable and accessible to all albeit slower alternative. A major drawback of the Hyperloop system is the low passenger capacity (28 to 56) per pod and the way to achieve the required passenger capacity per hour to compete with Rail and Aviation could be to increase the number of pods running per hour. Hyperloop nonetheless has the potential to become more affordable taking benefit of economies of scale if a large Hyperloop track network is built across Europe.

6.1 Limitations and future work

The results of this study should be viewed from the context of the limited number of criteria and the small system boundary due to which the effects on the larger European system boundary were not included. While the scoring was done in an objective manner, the risk of bias cannot be ruled out entirely which becomes a limitation of this study. A way to overcome this in a future study could be asking a panel of multidisciplinary experts to score on each criteria and taking an average of all the scores. This could be achieved by collecting the individual expert scores through digital surveys such as the ones used in this study. As Hyperloop is not yet commercially deployed there exists some uncertainty in the data available for Hyperloop as most of it is in the form of estimated data.

Due to the perceived increased attractiveness of smaller airports if Hyperloop was built, there could also be rebound effects of increased usage of aircraft and hence increased emissions from these airports for connections outside the region. However, as the system boundary was limited to the flights between these 4 airports such rebound effects were not considered. This limitation could be addressed in a future study with a wider system boundary. During the assessment of the "Affordability" subcriteria, estimated prices were used for Hyperloop and actual market prices were used for rail and aviation. State subsidies if any were not taken into account. The impact of state subsidies on the ticket prices of hyperloop, rail, aviation could be explored in a future study. "Equitable access" and "Affordability" were closely linked together because if the ticket prices were higher (as was estimated for Hyperloop) it directly limited the access to premium paying passengers only. This linkage was not elaborated further and both were treated independently as equitable access also considered disability access which was not directly related to cost.

When assessing the "Reliability" subcriteria, the main focus was on comparing weather based reliability. General system uptime figures and other maintenance related aspects were not considered for the alternatives. A challenge faced while assessing the "Land-use" criteria was that the comparable data for direct land-use for the three alternatives was scarce. Estimated data was available for land used by the line infrastructure for the alternatives and certain calculations with assumptions were required to make this data comparable across the alternatives.

Comparable data was available only for the estimated direct CO_2 emissions for the 3 alternatives and this was used for comparison in the "Emissions" criteria. These estimated emissions were only available for the operations phase and emissions from other lifecycle stages such as from the construction phase were not included. While the absolute values of direct operational CO_2 emissions were compared, the high altitude effects of Aviation emissions such as radiative forcing were not considered. If these high altitude effects were to be considered, Aviation scores for emissions could have been lowered further. The comparable figures for the total CO_2 emissions figures including indirect emissions over the entire lifecycle of the transport alternatives were not available and hence these could be found out through a separate Life Cycle assessment (LCA) study in future. The scores for the emissions criteria might differ significantly if the total lifecycle emissions were to be considered.

Another limitation was the lack of availability of prioritized transport objectives data for city municipalities which led to certain assumptions being made during the weighting process. This could be addressed in future studies through conducting digital surveys for different city municipalities. The additionally identified criterias “Innovation” and “Decongestion of roads” were excluded from this project because the objectives were too wide in nature and that less comparable qualitative and quantitative data was available. These could also be considered in a future study.

In this study, not all social aspects were considered from the UN SDGs (e.g. SDG 8 “Decent Work and Economic Growth”, SDG 10 “Reduced Inequalities”, SDG 11 “Sustainable Cities and Communities”)(United Nations, 2020). The only environmental impacts compared in the MCA were “Emissions” and “Land-use” and other environmental impacts from the Planetary boundaries concept(Rockström, et al., 2009) were not studied (e.g. biodiversity loss, ocean acidification, freshwater use, ozone depletion). A Social Impact Assessment (SIA) and Environmental Impact Assessment (EIA) could be carried out to study the above social and environmental aspects in detail before deciding to construct a new Hyperloop project in the region.

6.2 Ethical considerations

This project was purely academic in nature and its intention was to answer the research question without any personal benefit. Throughout this project work, ethical considerations were made and the impartial scientific process was followed. Despite the risk of bias during the scoring process for different alternatives, all the gathered qualitative and quantitative data and its comparative analysis has been performed based on the merits of each alternative with as impartial and neutral mindset as possible. This project also involved digital surveys which were voluntary and completely anonymous in nature, and were conducted ensuring that people’s rights were not violated. The results from surveys were directly used without modification in an objective manner to reduce the possibility of bias.

6.3 Conclusion

The Hyperloop was ranked as the best transport alternative in this study, closely followed by Rail, and Aviation was ranked last. Within the social criteria, Hyperloop was ranked best whereas within socio-economic and environmental criteria, Rail was ranked as the best alternative. While Hyperloop appears to be a quite promising new transport technology with recently successful low speed human passenger tests carried out in the U.S.A, it is still under development and there are several safety aspects that need further consideration. This MCA could be useful as an aid to decision makers for any similar Hyperloop transport projects within Europe.

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Appendix A

Note: Relevant objectives mentioned in quotes in the Appendix Table A are taken directly from the below referenced plans/reports/policies. These objectives and targets were used only to derive the Criteria. Only the derived 6 Criteria were used in this study.

Appendix Table A: Detailed objectives and Targets used to Derive Criteria.

In this study the Criteria were derived from the relevant Objectives/Targets in the plans/reports/ policies/goals listed in this table (Only the derived Criteria were used in this study)	**Relevant Objectives were taken from the transport and development plans/reports/policies** (Federal Ministry of Transport and Digital Infrastructure, 2016; Ministry of Infrastructure and Water Management et al., 2019;Government of the Netherlands, 2020b;European Commission, 2011;MRA Bureau, 2020)	**Objective Details were taken from the transport and development plans/reports/policies** (Federal Ministry of Transport and Digital Infrastructure, 2016; Ministry of Infrastructure and Water Management et al., 2019;Government of the Netherlands, 2020b;European Commission, 2011;MRA Bureau, 2020)	**Related UN SDG Targets and Indicators were taken from the UN Sustainable Development Goals** (United Nations, 2020;United Nations, 2020b;United Nations, 2020c;United Nations, 2020d;United Nations, 2020e)
Social Criteria			
1.Safety (measured as number of accidents, other safety aspects)	"*•Enhance transport safety (Federal Ministry of Transport and Digital Infrastructure, 2016)* *•While intensifying public transport we will also seek ongoing improvements to safety and quality of life in surrounding areas.*"(Ministry of Infrastructure and Water Management et al., 2019) *"•Safe public transport* *•Travelling in comfort by public transport"* (Government of the Netherlands, 2020b)	*"•Maintain, replace and modernize the structural fabric* *•Shift traffic to parts of the network and transport routes with a higher level of safety"*(Federal Ministry of Transport and Digital Infrastructure, 2016) *"•Safety on and around the tracks* *•Tackling aggressive behaviour"* (Government of the Netherlands, 2020b)	<u>*"SDG 3*</u> *"Ensure healthy lives and promote well-being for all at all ages"* <u>*"Target 3.6*</u> *"By 2020, halve the number of global deaths and injuries from road traffic accidents"* <u>*"Indicator 3.6.1*</u> *Death rate due to road traffic injuries"* (United Nations, 2020b)

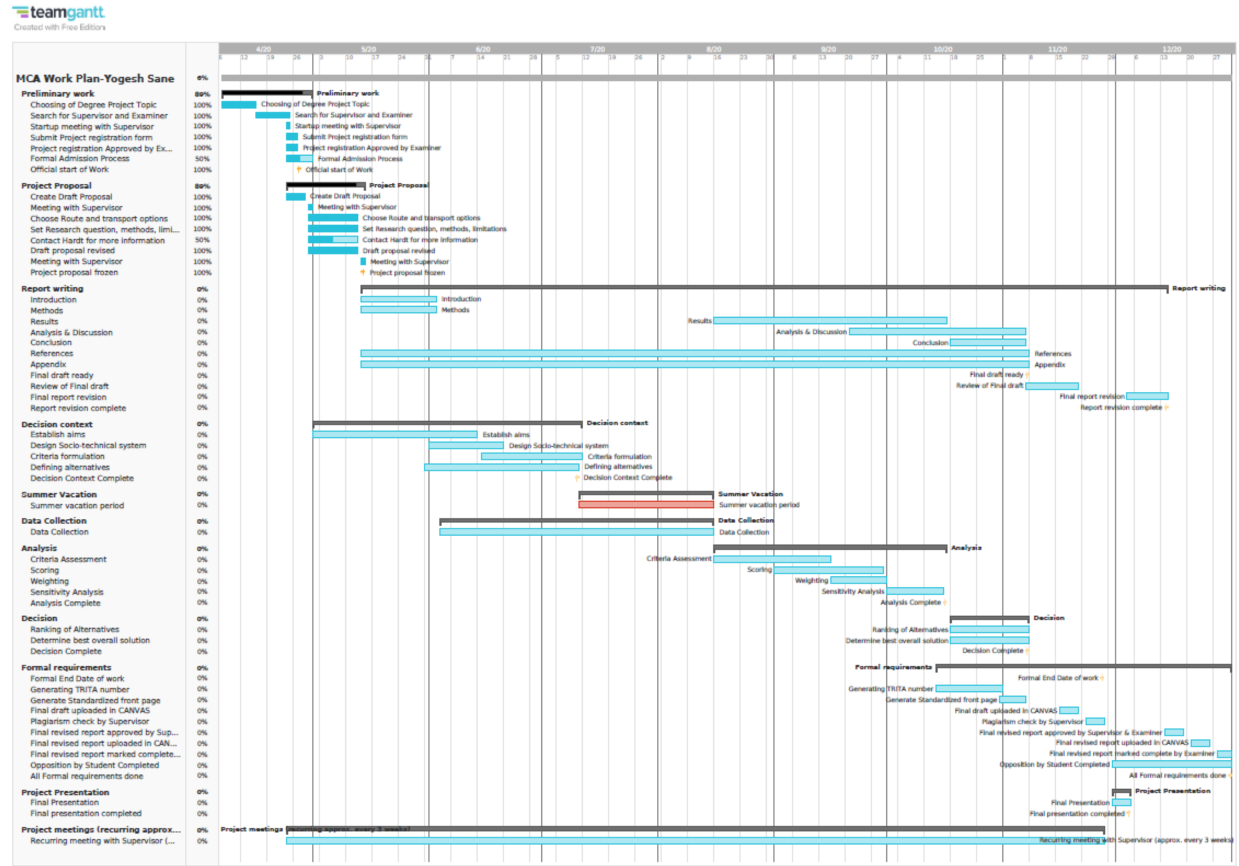
2.Noise (measured as decibel (dB))	*"•Improve the quality of life, including the noise situation, in towns, cities and regions"* (Federal Ministry of Transport and Digital Infrastructure, 2016)	*"•Prevent and reduce noise* *•Ease the burden on places and people/unlock urban development potential"*(Federal Ministry of Transport and Digital Infrastructure, 2016)	
3.Travel time (measured as journey time between destinations)	*"•Better public transport connections* *•Cross-border public transport"*(Government of the Netherlands, 2020b) *"•Facilitate mobility in passenger transport"*(Federal Ministry of Transport and Digital Infrastructure, 2016)	*"•Fast, sustainable connections between the Netherlands and the main economic hubs in our neighbouring countries"* (Ministry of Infrastructure and Water Management et al., 2019) *"•Maintain, replace and modernize the structural fabric* *•Improve the flow of traffic/remove bottlenecks (incl. traffic management)* *•Improve accessibility/quality of links"*(Federal Ministry of Transport and Digital Infrastructure, 2016)	
In this study the Criteria were derived from the relevant Objectives/Targets in the plans/reports/ policies/goals listed in this table	**Relevant Objectives were taken from the transport and development plans/reports/policies** (Federal Ministry of Transport and Digital Infrastructure, 2016; Ministry of Infrastructure and Water Management et al., 2019;Government of the Netherlands, 2020b;European Commission, 2011;MRA Bureau, 2020)	**Objective Details were taken from the transport and development plans/reports/policies** (Federal Ministry of Transport and Digital Infrastructure, 2016; Ministry of Infrastructure and Water Management et al., 2019;Government of the Netherlands, 2020b;European Commission, 2011;MRA Bureau, 2020)	**Related UN SDG Targets and Indicators were taken from the UN Sustainable Development Goals** (United Nations, 2020;United Nations, 2020b;United Nations, 2020c;United Nations, 2020d;United Nations, 2020e)

Socio-Economic Criteria			
4.Connectivity (measured as affordability, equitable access, better airport connectivity)	*"•Ensure the supply of goods, enhance the competitiveness of enterprises* *•By 2050, connect all core network airports to the rail network, preferably highspeed"* (European Commission, 2011) *"•Better public transport connections* *•Cross-border public transport"*(Government of the Netherlands, 2020b) *"•the accessibility of top economic locations* *•the availability and affordability of mobility for all residents of the MRA"*(MRA Bureau, 2020)	*"•Maintain, replace and modernize the structural fabric* *•Reduce transport costs* *•Increase the reliability of transport operations* *•Improve the flow of traffic/remove bottlenecks (incl. traffic management)* *•Improve accessibility/quality of links* *•Improve links to and from intermodal hubs (e.g. airports, seaports or combined transport terminals)"*(Federal Ministry of Transport and Digital Infrastructure, 2016) *"•Connections with the border regions* *•Fast, sustainable connections between the Netherlands and the main economic hubs in our neighbouring countries"*(Ministry of Infrastructure and Water Management et al., 2019)	*"SDG 9* *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation* *Target 9.1* *Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all* *Indicator 9.1.2* *Passenger and freight volumes, by mode of transport"*(United Nations, 2020c)
In this study the Criteria were derived from the relevant Objectives/Targets in the plans/reports/policies/goals listed in this table	**Relevant Objectives were taken from the transport and development plans/reports/policies** (Federal Ministry of Transport and Digital Infrastructure, 2016; Ministry of Infrastructure and Water Management et al., 2019;Government of the Netherlands, 2020b;European	**Objective Details were taken from the transport and development plans/reports/policies** (Federal Ministry of Transport and Digital Infrastructure, 2016; Ministry of Infrastructure and Water Management et al., 2019;Government of the Netherlands, 2020b;European	**Related UN SDG Targets and Indicators were taken from the UN Sustainable Development Goals** (United Nations, 2020;United Nations, 2020b;United Nations, 2020c;United Nations, 2020d;United Nations, 2020e)

	Commission, 2011;MRA Bureau, 2020)	Commission, 2011;MRA Bureau, 2020)	
Environmental Criteria			
5.Emissions (measured as direct CO_2 equivalent emissions per passenger per km)	*"•Reduce emissions of pollutants and greenhouse gases"*(Federal Ministry of Transport and Digital Infrastructure, 2016) *"•Reduce Europe's dependence on imported oil and cut carbon emissions in transport by 60% by 2050"* (European Commission, 2011) *"•The entire public transport sector will be emission-free and circular."*(Ministry of Infrastructure and Water Management et al., 2019) *"•Sustainable public transport"*(Government of the Netherlands, 2020b)	*"•Improve the flow of traffic/remove bottlenecks (incl. traffic management)* *•Shift traffic to low-emission transport modes* *•Maintain, replace and modernize the structural fabric* *•The sector will be practically emission-free by 2030 and fully circular by 2050.* *•By 2030, all public transport operators will operate fully on green electricity and will have adopted the principles of circularity in construction and maintenance and in managing services."*(Federal Ministry of Transport and Digital Infrastructure, 2016) *"•Public transport as an alternative to the car* *•Cleaner and more energy-efficient public transport* *•Sustainable stations"* (Government of the Netherlands, 2020b)	<u>*"SDG 13*</u> *Take urgent action to combat climate change and its impacts* <u>*Target 13.2*</u> *Integrate climate change measures into national policies, strategies and planning"* (United Nations, 2020d)
6.Land-use (measured as land used per km of infrastructure)	*"•Limit the impact on nature and the landscape"*(Federal Ministry of Transport and Digital Infrastructure, 2016)	*"•Limit additional land take* *•Avoid additional losses of unfragmented areas"* (Federal Ministry of Transport and Digital Infrastructure, 2016)	<u>*"SDG 15*</u> *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land*

			degradation and halt biodiversity loss *<u>Target 15.3</u>* *By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world* *<u>Indicator 15.3.1</u>* *Proportion of land that is degraded over total land area"* (United Nations, 2020e)

Appendix B



Appendix Figure B. MCA Work Plan created using the online tool by TeamGantt (2020) to track the MCA process in a given time.