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ÚSTAV JAZYKŮ

HYPERLOOP – MIRAGE OR USEFUL TECHNOLOGY OF THE FUTURE? A LITERATURE/INFORMATION SEARCH STUDY

HYPERLOOP – PŘELUD NEBO UŽITEČNÁ TECHNOLOGIE BUDOUCNOSTI - REŠERŠE DOSTUPNÝCH INFORMACÍ

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

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Bakalářská práce

Bakalářský studijní obor **Angličtina v elektrotechnice a informatice**

Ústav jazyků

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NÁZEV TÉMATU

Hyperloop – přelud nebo užitečná technologie budoucnosti - rešerse dostupných informací

POKYNY PRO VYPRACOVÁNÍ:

Proveďte rešerši dostupné literatury zabývající transportním systému hyperloop. Pokryjte Historii, technický koncept, současný stav, zhodnoťte, proč prozatím nedošlo k jeho nasazení v reálném světě a nastiňte možnosti budoucího vývoje.

DOPORUČENÁ LITERATURA:

Misha S., Hyperloop and Maglev: Future of Transport, 2022, Independently published , 101 str. ISBN: 979-8838966810

Kane E.,: Important Innovations: Transportation: Exciting Innovations Changing Your Future (Latest travel innovations including flying cars, hyperloops & hypersonic jets), 2018, Independently published, 75 str. ISBN-13 : 978-1728734507

HANSEN, Ingo A. Hyperloop transport technology assessment and system analysis. Transportation planning and technology [online]. Abingdon: Routledge, 2020, 43(8), 803-820 [cit. 2022-09-16]. ISSN 0308-1060. Dostupné z: doi:10.1080/03081060.2020.1828935

ABDELRAHMAN, Ahmed S, Jawwad SAYEED a Mohamed Z YOUSSEF. Hyperloop Transportation System: Analysis, Design, Control, and Implementation. _IEEE transactions on industrial electronics (1982)_ [online]. New York: IEEE, 2018, **65**(9), 7427-7436 [cit. 2022-09-16]. ISSN 0278-0046. Dostupné z: doi:10.1109/TIE.2017.2777412

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UPOZORNĚNÍ:

Abstract

This bachelor's thesis is focused on revolutionary technology called hyperloop. Aim of this thesis is to bring together relevant information about the concept of hyperloop. The thesis covers a brief history beginning with first concept of hyperloop, core infrastructure explanation and list of technologies used in the concept. Furthermore, chosen companies working on hyperloop technology are listed together with their accomplishments and designs. Thesis is closed with list of problems and challenges that development of hyperloop is dealing with, projects under development and brief look into the future.

Keywords

hyperloop, pneumatics, Elon Musk, maglev, magnetic levitation, traveling

Abstrakt

Tato bakalářská práce je zaměřena na revoluční technologii zvanou hyperloop. Cílem této práce je shromáždění relevantních informací o konceptu hyperloopu. Práce se zabývá stručnou historií hyperloopu počínaje prvním konceptem hyperloopu, vysvětlením základní infrastruktury a výčtem technologií použitých v tomto konceptu. Dále jsou uvedené vybrané společnosti pracující na technologii hyperloopu spolu s jejich úspěchy a návrhy. Práci uzavírá výčet problémů a výzev, se kterými se vývoj hyperloopu potýká, projekty, které prochází vývojem a stručný pohled do budoucnosti.

Klíčová slova

hyperloop, pneumatika, Elon Musk, maglev, magnetická levitace, cestování

Rozšířený abstrakt

Doprava z bodu A do bodu B se téměř neodlučitelně stala součástí našeho každodenního života. Nároky na dopravu stoupají, ať už v rámci spolehlivosti, šetrnosti k životnímu prostředí, rychlosti, nebo třeba ceny. V roce 2012 Elon Musk z frustrace po zhlédnutí plánů na stavbu nové vysokorychlostní vlakové trati oprášil myšlenky z dob minulých, a představil lidstvu a vědecké scéně nový koncept vysokorychlostní dopravy, který by mohl znamenat revoluci v dopravě. Tento koncept, nazvaný „hyperloop“, slibuje rychlejší, levnější a šetrnější dopravu pro životní prostředí. Má potenciál stát se řešením pro velké množství lidí, kteří tráví na každodenní cestě do zaměstnání dlouhé hodiny. Cílem hyperloopu je dosahovat rychlostí přes 1000 kilometrů za hodinu, což by z něj dělalo nejrychlejší možný způsob dopravy, vyjma dopravy letecké. Celý koncept je velmi jednoduchý, skládá se z vozidla, nazývaného kapsle, které cestuje uvnitř tubusu za pomocí magnetické levitace, podobně jako japonské rychlovlaky. Jediný rozdíl oproti těmto vlakům je, že uvnitř tubusu je prostředí s velmi nízkým tlakem neboli téměř vakuem, které pomáhá snížit odpor vzduchu, což dohromady s odstraněním valivého odporu za pomocí zmíněné magnetické levitace dává hyperloopu výhodu oproti ostatním pozemním způsobům transportu. I přes svůj slibný potenciál stále existuje množství technických a infrastrukturních výzev, které je třeba překonat, než se hyperlop stane realitou.

Tato bakalářská práce důkladně prozkoumává hyperloop, revoluční dopravní koncept, který uchvátil představivost výzkumníků, inženýrů a vizionářů po celém světě. Cílem bakalářské práce je provést rešerši dostupných informací, a na základě těchto zjištěných informací zhodnotit skutečný potenciál tohoto inovativního dopravního systému a posoudit, zda je hyperloop pouze fantazií, nebo zda má tato technologie potenciál na realizaci. K získání potřebných informací byly využity z velké části internetové zdroje, odborné publikace a jedna stěžejní kniha.

Bakalářská práce je strukturována do čtyř hlavních kapitol. Kapitola první mapuje historické pozadí této technologie, již od dob prvních návrhů, které se hyperloopu podobají. Kapitola je rozčleněna do podkapitol dle století, počínaje sekcí o 19. století, která zmiňuje koncept George Medhursta, jež přišel s nápadem cestování skrz tunely. Dále jsou zde zmíněny vybrané experimenty a projekty z 19. století. V podsekci o 20.

století je zmíněn první design hyperloopu, který bohužel nebyl nikdy zrealizován, ale již obsahoval základní prvky hyperloopu. Je zde také zmíněn první úspěšný levitační vlak z roku 1914. Poté jsou zde zmíněny projekty francouzských inženýrů a výzkumníků z MIT. Poslední podkapitola obsahuje zmínku o jednom prototypu hyperloopu ze začátku tisíciletí a je uzavřena publikací Elona Muska, který začal psát moderní historii hyperloopu.

V kapitole technologický koncept je vysvětlen základní princip fungování hyperloopu a vize Elona Muska, jsou zde také vysvětleny stěžejní části infrastruktury – tubus a kapsle, a jejich stručné specifikace. Dále jsou zde popsány v podkapitolách jednotlivé technologie, které hyperloop využívá. Je zde zmíněno, proč je technologie „switching tubes“ nutností, aby nebyla celá síť limitována. Je zde vysvětlen princip fungování magnetické levitace a elektromagnetického pohonu, který hyperloop nejspíše bude využívat. Jedna z technologii jsou také vakuové pumpy, které jsou taktéž jednou z velice důležitých technologií pro správné fungování celé infrastruktury, a budou muset být přítomny podél celé infrastruktury. Nachází se zde i sekce o navrhovaném provozu, která nabízí návrhy o provozních rychlostech, přetížení, operačních vzdálenost a energetické efektivitě. V podsekci o bezpečnosti jsou vysvětleny některé otázky široké veřejnosti, je zde rozebráno i zabezpečení tubusu a kapsle uvnitř něj. Kapitola je uzavřena sekcí, která pojednává o snížení emisí, kterého hyperloop může dosáhnout.

Další kapitola pojednává o aktuálním stavu vývoje. Jsou zde zmíněny vybrané firmy, které momentálně pracují na tomto novém způsobu dopravy. Jsou zde krátce popsané jejich prozatím dosažené výsledky vývoje této technologie a technologické pokroky. Taktéž je zde zmíněn program, kterého se účastní několik ze zmíněných firem, a má být nápomocen při dalším vývoji hyperloopu. Kapitola taktéž zmiňuje vize jednotlivých firem a práce, které probíhají. Závěrem je v téhle kapitole uvedena odhadovaná cena implementace a sekce o poptávce po tomto způsobu dopravy.

Poslední, čtvrtá kapitola má za cíl nastínit budoucí vývoj technologie. První podkapitola zmiňuje problémy, se kterými se momentální vývoj potýká, jako například udržitelnost vakua a design stanic. Další bariérou v implementaci je samotná cena implementace, standardizace hyperloop sítě a taktéž potřeba propojení s existující dopravní infrastrukturou. Zmiňuje také nutnost potřeby bezpečnostních standardů alespoň srovnatelných s těmi v letectví. V druhé sekci čtvrté kapitoly jsou zmíněny plánované projekty jednotlivých firem, práce je poté uzavřena možným budoucím vývojem a pohledem do budoucnosti, který je z důvodu momentálního stavu vývoje, nejasný.

Hyperloop je bezpochyby fascinující a inovativní koncept dopravy, který má potenciál zlepšit naši mobilitu a přinést mnoho výhod. Bude zajímavé sledovat, jak se tato technologie bude dále rozvíjet a jaké dopady bude mít na naše každodenní cestování v budoucnosti.

Bibliographic citation

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Author's Declaration

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I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the project and listed in the comprehensive bibliography at the end of the project.

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Brno, May 30, 2023

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author's signature

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Brno, May 30, 2023 --

Author’s signature

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INTRODUCTION

The aim of this thesis is to research available materials and information about hyperloop, which can, at some point in the future, be successor of Maglev system, probably the fastest way to travel on the surface of earth.

The amount of people living on the earth is increasing every day, leading to a growing demand for transportation. Millions of people commute to work daily, many of them spending long hours on the road. The concept of hyperloop, often referred to as the fifth mode of transportation may potentially help to solve this problem. Hyperloop is, and for some time, will remain just a concept of high-speed transportation system for passengers and cargo, popularized by Elon Musk in 2012. Over the last decade, number of companies got involved in making this new technology a reality.

Concept consists of capsules travelling inside a tube, levitating above the track. Technology used for levitation is called magnetic levitation. This may sound unrealistic, but it is not levitation in the true sense of the word. Magnetic levitation technology is already used in mentioned Maglev trains in Japan. Maglev trains and hyperloop differ in one thing – low-pressure inside the tube of hyperloop, close to vacuum. Because of that, hyperloop is said to reach speeds exceeding 1000 km/h with minimal energy use, on the contrary, Maglev can travel beyond 400 km/h but would suffer extreme energy loss due to air resistance. One of hyperloop aims is also to be cheaper, faster, and more environmentally friendly than other options of travel.

Thesis begins with historical pat, starting with the very first idea of hyperloop and progressing through different significant milestones. Different pieces of technology used in the hyperloop system are discussed, while shedding light on the various components and advancements in technology. Additionally, efficiency and safety feature of hyperloop will be touched upon, emphasizing their significance. Furthermore, current state of development is analysed, providing insight into the efforts of different companies and their respective progress in advancing the hyperloop technology. In the final chapter of this paper, potential future development of this groundbreaking technology is outlined. Ongoing projects are highlighted, together with planned routes. By analysing these various aspects, this paper aims to present a comprehensive analysis of the hyperloop, shedding light on its evolution, current status and prospects for the future.

1. HISTORY OF HYPERLOOP

Using pneumatics as a technology to send objects somewhere has been in people's minds for quite a long time, more precisely, since Greek antiquity, but no one has ever thought about using it as a public transport (Thompson, 2015). As I already mentioned, Elon Musk is not a man behind the whole hyperloop idea, he just made it way more popular than it was. His idea of hyperloop is based on studies three centuries long (Macola, 2021).

1.1 19th century – first idea

The very first concept resembling hyperloop came from inventive mind of George Medhurst, who was mechanical engineer, born in Great Britain, pioneer of utilization of compressed air in terms of propulsion. He was the first one to speculate, that perhaps we can blow cargo with passengers through the tunnel. In 1799, he proposed an idea to move goods through cast-iron pipes with air pressure. (Garber, 2013; Macola, 2021; Oullette, 2011)

Actually, in 1844-1845, there was an experimental cargo station, built by *London and Croydon Railway*, with vacuum created between the rail and the train which caused it to be propelled forward thanks to atmospheric pressure. Unfortunately, the experiment was abandoned after approximately 2 years, due to the challenges associated with maintaining high pressure in the tube and valves requiring unaffordable levels of maintenance (Mansfield, 2010). On the other hand, at the beginning of 1850s, pneumatic cargo railways were built in other parts of Europe, such as Dublin, Paris, and again in London. (Macola, 2021; Garfield, 2018)

Pneumatic railway built by The London Pneumatic Despatch in London system built in London was meant to carry parcels, but Duke of Buckingham and several other members of company demonstrated, that it was large enough to carry people too, when they travelled through it in 1865 (Garfield, 2018; Oullette, 2011). That was around the same time, when Jules Verne published "Paris in the 20th Century", with vision of tube trains stretching through the Atlantic Ocean.

There were many more concepts and designs constructed, such as 500 meters long *Crystal Palace Atmospheric Railway* (in some sources referred to as *Crystal Palace*

Pneumatic Railway) in south London (Macola, 2021; Gaber 2013) operating from August 1864 to October 1864 (Gresta, 2022) or *The Beach Pneumatic Transit* in New York (Gaber, 2013; Garfield, 2018), operating in Manhattan from 1870 to 1873 (Gresta, 2022), which were subway predecessors in the respective cities.
Before the turn of 20th century, a number of big cities used pneumatic tube systems for transporting mail (Garfield, 2018), with the Prague's one being probably the last one existing (Oullette, 2011).

1.2 20th century

At the beginning of 20th century, an article called 'The High-Speed Bet' was published by Robert Goddard, later published in Scientific American under the name 'The Limit of Rapid Transit' (Traynor, 2017). Goddard is also acknowledged by Elon Musk in his white paper, as one of the first to actually design a hyperloop. It included what is now thought of as one of the first designs of a hyperloop. In the article, he described, that train can travel from Boston to New York in 12 minutes. Unfortunately, it was never built, but it already mentioned some of the hyperloop's components, such as levitation pods and vacuum-sealed tube, which I will talk about later on. (Macola, 2021; Garfield, 2018; Garber, 2013)

First example of a magnetic levitation train was unveiled in 1914, by Émile Bachelet, a French American inventor. His aluminium trolley called *Levitating Transmitting Apparatus* measuring approximately one meter in length, demonstrated the ability to levitate one centimeter above an 11-meter-long track of magnets. The device captured significant attention from the media, earning it the moniker of the "flying train." Notably, even Winston Churchill was in attendance during the demonstration and reputedly said that it was the most wonderful thing he has ever seen. (Gresta, 2022)

In the aftermath of the genocidal event which we call World War II, French engineers, under the lead of scientist Jean Bertin tried to build something similar to the hyperloop. They called it the "Aerotrain", which was worked on since 1965 until 1977. Their prototype was very similar to levitation train, but opposed to it, it relied on cushions of air, whereas levitation train relied on magnetic resistance for propulsion. Bertin's aerotrain reportedly reached speeds over 400 km/h (Arbuckle, 2016). Unfortunately, as a consequence of insufficient funds, being too noisy in combination with oil crisis and sudden death of Jean Bertin in 1975, the project was abandoned in 1977. (Bonaventure, n.d.; Macola, 2021)

There was one more project in late 20th century. In the early 1990s, MIT researchers tried their luck. With Professor Ernst Frankel in the lead, they started their work on vacuum-tube train, which promised route from New York to Boston in 45 minutes (Macola, 2021; Garfield 2018).

As Stewart (2014) found, “The advantage of a vacuum tube is simple, you can achieve high speeds” (para. 8), according to Ernst Frankel. It is because there is little air resistance – trains in tunnels push a wall of air ahead of them, which creates energy loss. Eliminating the air resolves this issue, according to experiments carried out by Erns Frankel and his team. In order to find out, what velocities were obtainable, they built a half mile long tube at MIT and shot things through it. They went from ping pong balls and continued with mechanical models. Due to near vacuum environment within the tube, train could travel at speed up to 930 km/h, which is twice as fast as within an air filed tube. Professor Frankel stated that giant pumps keeping a near vacuum would be needed, each 20 to 30 miles apart, and that the main leakage would be caused by the end stations. (Stewart, 2014)

Prototype was built, but unfortunately, not finished because of huge cost of building the whole system, and proposed top speed was the same as the speed of already existing bullet trains in China and Japan (Stewart, 2014).

1.3 21st century

At the dawn of the century, CEO of US consortium ET3 Global Alliance Daryl Oster designed another hyperloop type of train, which was probably closest thing to Musk’s hyperloop, as we know it. It was a maglev train with car-sized pods inside, travelling in tubes, using linear electric motors for acceleration. (Garfield, 2018; Macola, 2021; Garber, 2013)

1.3.1 Elon Musk's contribution

When entrepreneur Elon Musk found out about construction of California High-Speed Rail in 2012, he was disappointed:

> *How could it be that the home of Silicon Valley and JPL – doing incredible things like indexing all the world's knowledge and putting rovers on Mars – would build a bullet train that is both one of the most expensive per mile and one of the slowest in the world?* (Musk, 2013, p. 1)

That is when he came up with the Hyperloop. It took him only about a year, until he revealed his first design, since first mentioning it in 2012, in the already mentioned document, known as the *Hyperloop Alpha white paper*.

Musk (2013) published the document with information about its construction. It was proposed to be a better alternative to the California high-speed rail, called "Bullet Train", connecting San Francisco and Los Angeles in just 35 minutes, with an estimated cost of 6 billion dollars. According to this document, the hyperloop was proposed to be cheaper and more energy efficient than other forms of transport. Musk did not patent it, because he considered Hyperloop Alpha to be only the starting point, therefore he registered the design instead for future scientific and engineering community to further develop his idea (Macola, 2021).

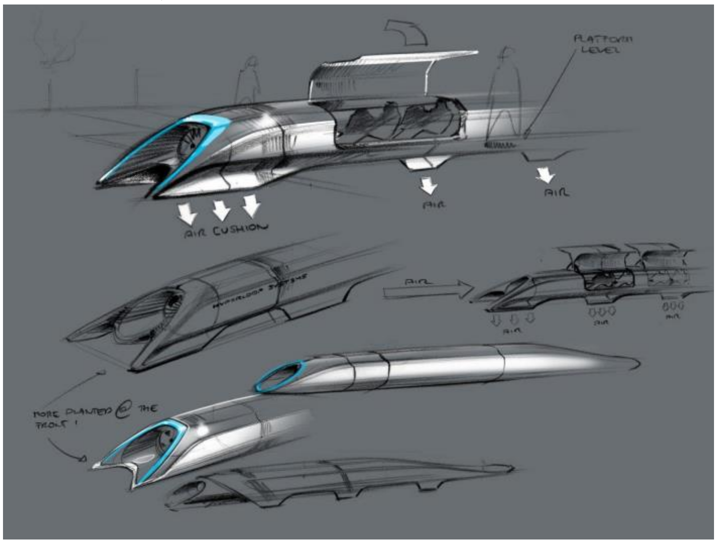

Fig. 1 - First concept of hyperloop (Musk, 2013)

Even though Musk was not behind any of the new companies, he still wanted to provide some assistance, hence SpaceX announced the SpaceX Hyperloop Pod Competition in 2015. This competition would allow teams to present their ideas, with the best pods having the chance to try SpaceX's Hyperloop test track. In just a week, competition received hundreds of applicants, while most of them being university student groups (Alba, 2017).

The first part of the competition was the Design Weekend, where each of the teams got a chance to present their designs, which were judged by a team of SpaceX judges. Judges selected 30 teams to build subscale prototypes and test them on SpaceX test track the following year. The competition was held in January 2017 at SpaceX's Hawthorne test track, where 27 teams arrived with their prototypes. Three best teams – MIT, Munich Technical University and Delft University of Technology got the opportunity to test their pods in the Hyperloop test track. (Alba, 2017)

The competition was so successful that it became an annual event. Over the years, competition has taken place 5 times, each time with different criteria to determine the winner. The most recent competition focused on the speedy and precise drilling of a tunnel. During the fourth competition in 2019, TUM Hyperloop, former and new winner, achieved top speed of 463 km/h, which is supposed to be the fastest test of hyperloop technology yet, as of January 2023 (Young, 2019).

2. TECHNOLOGICAL CONCEPT

2.1 Introduction and Elon Musk's idea

The basic idea of Hyperloop is a concept of vacuum train, utilizing magnetic levitation, moving in a network of tubes, with vacuum or nearly vacuum inside. Very similar to pneumatic mail. Elon Musk himself defined the hyperloop system as “a mix between Concorde, a rail gun and an air-hockey table.” (Stations of a near future: Experience within a Hyperloop Station, 2020)

Open design document called Hyperloop Alpha, created by Elon Musk in 2013 was the very first technological concept of Hyperloop, which many companies took inspiration from. The reason for Musk (2013) to work on something like that, is the already mentioned California high speed rail. In his document, he also emphasized that the new transportation system should be, among other things, safer, faster and sustainably self-powering. As Elon Musk (2013) stated, the only option for super-fast traveling on

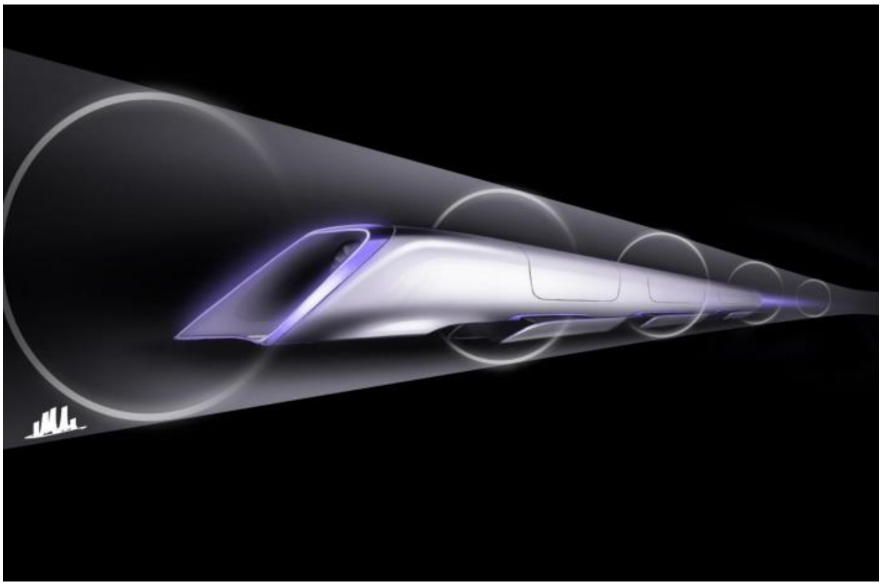

Fig. 2 - Visualization of capsule in tube (Musk, 2013)

the surface of earth is to build a tube that contains a specific environment – low pressure, with capsules or pods, transported throughout the tube.

Musk (2013) had proposed the idea that the capsules would float on a cushion of air, featuring pressurized air and aerodynamic lift. That is very similar to how pucks levitate above an air hockey table. The absence of wheels would eliminate rolling resistance, while the near vacuum environment would minimize air resistance. Each capsule would be equipped with an inlet fan and axial compressor located at the front, to pump the air from the front of the capsule. The capsules are accelerated via a magnetic linear accelerator affixed at various stations on the low-pressure tube with rotors contained in each capsule. Passengers may enter and exit hyperloop at stations located either at the ends of the tube, or branches along the tube length. In Hyperloop Alpha concept, pods were proposed to reach speeds of 1220km/h.

The companies, developing their own versions of hyperloop are not replicating Elon Musk's idea in all aspects, however, they are using very similar solutions. Instead of making the pod float on a cushion of air, these companies are working with MagLev technology, which Elon Musk considered expensive. This is due to the fact that MagLev technology provides numerous advantages, such as significantly larger "air gaps" between the capsule and the track, higher energy efficiency in levitation, and reduced maintenance expenses (Yao, 2023).

2.2 Main Infrastructure

Main components are very simple. It is a tunnel, which is called a 'tube' and the vehicle inside the tunnel, called 'pod' or 'capsule'.

Fig. 3 - Visualization of hyperloop in environment (Macola, 2021)

2.2.1 Tube

The basic design of hyperloop, that all companies are working with, is a low-pressure tube. Elon's alpha concept proposed a tube with a diameter of 2,23 meters (Musk, 2013), although, many companies are using tube with various diameters (Alba, 2017; Wright, 2016). As Delft Hyperloop mentioned in their report, due to need of room to store necessary technical parts of pod and to make an isle in the pod, diameter is assumed to be 3,5 meters (Kurstjens et al., 2022). HTT proposed diameters of 4,4; 5,6 and 4 meters (Cooper, 2018; Gresta, 2022). The primary materials used are mostly steel as proposed by Elon Musk himself (Musk, 2013; Nevomo, 2022a) as well as concrete, or combination of these two materials (Kumar et al., 2022). Both materials are preferred by

Fig. 4 - Hyperloop One's test track in Nevada (Edelstein, 2022)

developers, but are still undergoing testing for suitability in different environments. HTT experimented with carbon steel, but they decided to study new materials, due to carbon steel being expensive (Gresta, 2022).

Tubes can be constructed in 3 different vertical alignments – underground, on the ground, or elevated on pillars (as depicted on Fig. 4). The choice of alignment depends on the specific area where the tube will be installed. In nature reserves, it would be a suitable option to put tubes underground to minimize landscape disruption. In urban areas it might be beneficial to also build tubes underground to not interfere with existing infrastructure, or for that same reason above ground if the underground space is already occupied by existing infrastructure. On the other hand, in rural areas, tube elevated on pillars might be the best option as it saves on tunnelling costs and limits the disturbance of land. A complete assessment of the vertical alignment options has been made by Delft Hyperloop V (Delft Hyperloop V, 2021). If it would be elevated tube on pillars, looking similar to London's Overground, it would be 5 meter high, and pillars would be 30 meters from each other, or alternatively, 20 meters, as proposed by Bibop Gresta (2022).

Within the tube, a near-vacuum environment is established. Near-vacuum environment removes air resistance, therefore allows to achieve high speeds without using significant amounts of energy. Elon Musk (2013) put forward the idea of maintaining a pressure of 100 Pascals, while Gresta (2022) argues in his book, that a pressure range of 10 to 50 Pascal would be more efficient, as suggested by Carl Brockmeyer, an engineer from company credited with inventing vacuum pumps. To minimize air leakage, all stations, emergency exits, and branches throughout the hyperloop system are isolated from the main tube.

2.2.2 Pod/capsule

Pods are designed in various sizes and designs. For example, Hyperloop Transportation Technologies' pod is sized as an aircraft without wings, proposed to carry 28-48 passengers each, according to their official website (Hyperloop Transportation Technologies, 2022). Their version is constructed from specially made dual-layer smart

Fig. 5 - XP-1 – experimental pod of Hyperloop One (Walker, 2017)

composite material, which they call Vibranium, and consists of carbon fiber and embedded sensors. Gresta (2022) mentioned, that this carbon fiber compound offers flexibility 7 times bigger than that of aluminium, and strength 2 times bigger than steel. Sensors blended into the material can measure critical information, such as stability, temperature, and integrity in real time.

Hyperloop One has already made 2 different pods. One for full scale testing, and the second one for passenger testing, in scaled down version, named XP-1 and XP-2, which is shortcut for Experimental Pod 1, respectively 2. Pod for passenger testing, is made of aluminium and carbon fiber (Walker, 2017), measuring 8,7 meters, while being 2,7 meters tall and 2,4 meters wide (Cooper, 2017).

The construction of motor was difficult, because some of the electrical devices are not capable of operating, or struggle to operate in near-vacuum conditions (Cooper, 2017). In order to build the motor, which is one of the most efficient motors ever built, the team responsible for the construction built 500 motors prior to the full-scale test(s) (Cooper, 2017). The motor achieved 3,151 horsepower during one of the tests (Etherington, 2017).

Second pod, named XP-2 and nicknamed Pegasus, was made for passengers testing, created in collaboration with Bjarke Ingels Group and Kilo Design (Walter, 2020). This vehicle was designed with 2 seats, to demonstrate the safety of passengers in pod. XP-2 successfully transported its first passengers on November 8, 2020, after undergoing hundreds of tests prior to this event, reaching a speed of 172 km/h (Luczak, 2020). Unfortunately, I could not find specific information about the construction of XP-2, but I assume, it is constructed similarly to XP-1, likely using carbon fiber. Apart from this information mentioned above, there is not much detailed info known about different companies' capsules' construction to this date, other than usage of materials and brief description as of May 2023.

As Delft Hyperloop assumes, at the cruising speed of the pod, it would appear to passengers as if the surroundings were passing by at 1000 km/h. At this speed, buildings and trees would be reduced to a blur to the human eye, causing nausea and motion sickness, therefore, pods will not be supplied with windows (Kurstjens, et al., 2022).

2.3 Technology

2.3.1 Switching Tubes

This is arguably one of the more complex challenges for successfully building hyperloop system. Hardt Hyperloop company is trying to figure out this technological aspect, due to fact this technology is new and only so little is known about it. Without the ability to switch tubes, the whole network would be very limited, in other words, not having the ability to switch tubes will be very insufficient for the whole infrastructure. If hyperloop will become reality, millions of individuals will use hyperloop on a daily basis, meaning multiple platforms at different stations will have to be created for people to get in, same as on regular train stations. This technology in fact, exists, but it has not been tested at scale. Hyperloop developers rely on this technology to be possible, but as of now, it is in stages of early development. (Hardt Hyperloop, 2022b)

2.3.2 Magnetic levitation

Magnetic levitation, or MagLev, technology used in trains carrying the same name, is using electromagnetic forces between magnets on the vehicle and coils on the ground to levitate the vehicle above, or in another words, float. It is technology that was dismissed by Musk in his initial concept, due to cost, however, companies are using it as a solution for their versions of hyperloop.

How does magnetic levitation work?

The concept is quite straightforward. The properties of magnet are widely known. Opposite poles attract each other, same poles repel each other. Therefore, in magnetic levitation case, like poles are installed on bottom of the vehicle and on its track, pushing the vehicle upward and causing it to levitate. However, hyperloop uses magnetic levitation quite differently. In Musk's original concept, pods were proposed to float on cushion of air, but as mentioned, companies are using some form of magnetic levitation.

Fig. 6 - Example of magnetic levitation (How maglev works, 2016)

In case of Hyperloop Transportation Technologies, it is passive magnetic levitation. Magnets are placed on the underside of capsules same as in MagLev train, but in special configuration called *Halbach array* (Fig. 7), which makes the magnetic force of the magnets focus on one side of the array, thus creating magnetic field below the array, while almost cancelling out the field on the other side. As a result, this arrangement has the capability to generate levitation forces of approximately 40 metric tons per square meter (Gresta, 2022). This solution used by HTT is called Inductrack, invented by Professor Richard F. Post. He invented and tested Inductrack during 1990s, at General Atomic laboratory in San Diego. Subsequently, the remarkable invention has gotten attention of the US military and was classified for military application. After HTT started their project, professor Post himself contacted the company and helped to de-classify Inductrack from military to use it for civil purposes (Gresta, 2022). Thanks to reduced rolling resistance, due to utilizing magnetic levitation, pods use very little energy (Cassandra, 2020).

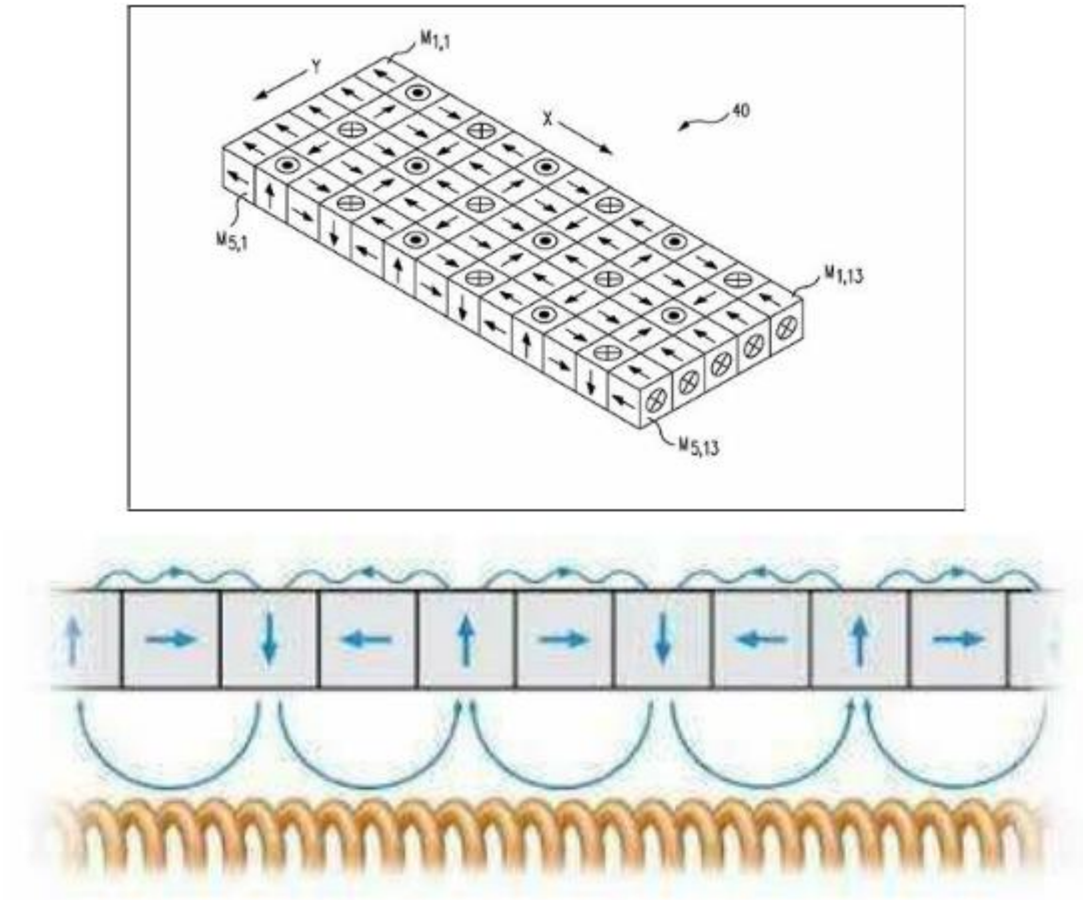

Fig. 7 - Hallbach Array (Gresta, 2022)

2.3.3 Electromagnetic propulsion

For pushing the vehicle forward, another form of magnetic levitation is used, and it is called electromagnetic propulsion. The vehicle is both pushed and pulled forward at

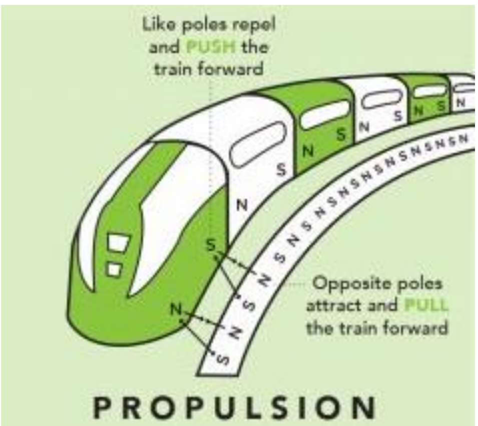

Fig. 8 - Magnetic propulsion (How maglev works, 2016)

the same time. Son of MagLev inventor said that “A Maglev train car is just a box with magnets on the four corners” (How maglev works, 2016, para. 5).

Which is helpful in explanation. Imagine one part of the train, with 2 north pole magnets at the front and 2 south pole magnets at the rear end. Once you electrify the propulsion loop, it will start to generate magnetic fields that will pull and push the train forward. This technology pushes the vehicle forward using electric energy only. Two different propulsion systems are being used in the development of hyperloop - the linear synchronous motor (LSM) and the linear induction motor (LIM). As Hardt Hyperloop (2022b) states, this linear electric engine is used only for achieving pod’s crusing speed, afterwards, only fraction of energy is needed.
(How maglev works, 2016)

2.3.4 Vacuum pumps

Already mentioned multiple times, hyperloop pods are proposed to travel through tubes with almost vacuum inside, meaning that there is almost no air. Therefore, device to pump the air out of the tube is needed. Technology used here is similar to technology that pumps water from low to high ground. Creating almost near vacuum will reduce drag force of the air by 1000 times relative to sea level conditions (Hennessey, 2019; Musk, 2013), which is major advantage of hyperloop, compared to another forms of transport. In other words, air pressures inside the tube are equal to air pressures at high altitudes (Cortese, 2018; Musk, 2013). This pumps, sized as a containers (Hardt Hyperloop, 2022b), need to be placed every few kilometres. According to Hyperloop Transportation Technologies (2022), every 10 kilometres. As Gresta (2022) stated in his book, the process of depressurization of a 10-kilometer-long tube takes approximately 16 hours. Following this, the system transitions into a maintenance mode, where only 5 to 10 % is needed to sustain the desired pressure within the pipe.

2.4 Operations

2.4.1 Speed characteristics

According to Delft Hyperloop, average cruising speed of the hyperloop's pod will be 1000 km/h. Reaching this speed will be achieved using linear motor, without using its maximum acceleration rate for the sake of passenger's comfort. This implies, that large distance will be needed for acceleration so that passengers can experience smooth acceleration, which would be comparable with those of already existing high-speed train(s). According to AECOM (2020), maximum acceleration should be 0.1G, which is still much lower compared to travelling in airplane, where passengers can experience up to 1.3G. (How Much G-Force Can The Human Body Withstand?, 2021)

Another time passengers are going to experience gravitational forces is during turns. Maximal lateral acceleration, according to Delf Hyperloop, is set to 0.4 G due to passenger's comfort, (Santangelo, 2018; AECOM, 2020; Bae et al., 2020) from which the smallest radius of the turn at full speed is calculated: 19,7 kilometres. Bibop Gresta proposed 0.5 G lateral in his book. (Gresta, 2022)

On the other hand, G-forces during emergency deceleration would be higher. Delft proposed that G-force during emergency deceleration would be 1G (AECOM, 2020), with assumption that all passengers are wearing seat belt. This deceleration speed means that 28 seconds will be needed for pod to make a full stop from going 1000 km/h, meaning pod frequency during the rush hour being 30 seconds per one pod is absolute safety maximum. Hardt Hyperloop's proposed emergency brake deceleration is up to 1,2G (Hardt Hyperloop, 2022c).

2.4.2 Operational distances

Hyperloop is said to use hardly any energy while traveling at a constant speed, it is obvious that traveling longer distances is way more efficient than short distances, because of the distance needed for acceleration and deceleration. Minimum distance proposed by Delft is 100 km, with 20% of the journey travelled at cruising speed. In terms of efficiency, the maximum length of a hyperloop corridor can also be identified. This is assumed to be $l_{max,corridor}$ = 1500 km. After a distance of around 1500 km the energy consumption per km per passenger of an airplane starts to drop rapidly to a level at which they can compete with a hyperloop on an economic level, in speed and eventually in energy consumption (Musk, 2013; Federici et al., 2009).

2.4.3 Energy efficiency

With usage of magnetic levitation and near-vacuum environment, rolling and air resistance forces minimized, hyperloop is said to be most energy efficient mode of transport, with energy consumption being comparable to a high-speed train. The majority of energy consumption in hyperloop system is done by propulsion and vacuum pumps. Accurate calculations do not exist yet, because no hyperloop system has been built yet, but some estimations exist. Hardt Hyperloop estimates this number of their hyperloop system to be 38 Wh/passenger/km (Dabrowska et. al., 2021). US Department of Energy estimates daily consumption of 3 different corridors from 105 to 173 Wh/passenger/km (Department of Energy et al., 2021), with size of tube making the difference, as Department of Energy is using tube wider by 0.5 meter in diameter. For comparison, a high-speed train uses from 80 to 120 Wh/Passenger/km and airplane uses between 350 and 520 Wh/passenger/kilometer (Dabrowska et. al., 2021, Janic, 2020), showing that concept of hyperloop is way more efficient in terms of distance/energy consumption. According to Hardt Hyperloop (2022b), “The energy used for traveling with the hyperloop is 10x lower than for road transport or aviation, including the energy to pump down the tubes.”

In a book written by Gresta (2022), feasibility study with usage of solar panels is mentioned on page 121. On a 100-kilometer-long track, with a solar panel efficiency of 21.5%, 244,000 MW of energy will be generated, which is supposedly almost 30,000 MW more than is needed for hyperloop. Gresta then suggests, that residual energy can be used to power homes.

2.5 Safety

If you think about the idea of people being shot through tube at high speeds, you will maybe begin questioning yourself, if it is safe. Whether there is a system failure of hyperloop, or weather impact. Citing straight from Musk's Hyperloop Alpha paper, "The design of Hyperloop has been considered from the start with safety in mind" (Musk, 2013, p. 53). Taken from Hardt Hyperloop official page, one of the companies which is currently working on hyperloop:

> *Hyperloop is being developed in a collaborative way, with safety as the highest priority. Specialized companies are involved on every aspect and component, and governments, research and knowledge institutions and standardization organizations are involved in aspects such as the establishment of hyperloop safety and interoperability standards.* (Hardt Hyperloop, 2022c)

Hyperloop will have no windows, therefore you can think, what the physical experience of acceleration and the high speeds will be. According to Hardt Hyperloop (2022c) official page, accelerations and deceleration will be smooth, because they will happen over large distances. On top of that they say that it will feel same as in airplane. "Once the vehicle is at full speed passengers will not notice the speed, same as when flying on an airplane. " (Hardt Hyperloop, 2022c). Another fact taken into consideration is, that none of the companies working on hyperloop is working on hyperloop with piloted vehicle inside. Instead of that, the vehicle will be operated autonomously. In fact, those vehicles will not have to cross any traffic as we do daily in cars, thanks to its environment.

Magnetic field, being present in hyperloop, will not do any harm to a human being either. "A person holding a fridge magnet will experience multiple orders of magnitude stronger magnetic fields then in the Hyperloop." (Hardt Hyperloop, 2022c).

The possibility of an accident occurring within the hyperloop system needs careful consideration. Due to the absence of breathable air within the hyperloop tube, safety protocols must take this into account and devise appropriate solutions. In the event of an incident, the procedures are very similar to that on an airplane. As described by Hardt Hyperloop (2022c), "The pressure in the vehicle will drop over time to the pressure in the pipe. Oxygen masks will fall to provide oxygen while the vehicle will come to a safe and quick standstill."

Safety of the tube

Safety is an important aspect, in every mode of transportation. With hyperloop being a new concept and still under development, safety standards and emergency protocols are still being developed.

Challenge here is the vacuum tube environment. Passengers cannot just walk out of the pod when there is an emergency. Delft proposes something which is called "safe haven" concept. As there are emergency lines along highways, there would be emergency tubes alongside main tube(s) with emergency exit included. In case of emergency, pods can move into a safe haven, which then (partially) pressurizes to enable passengers to leave the tube.

Sturdiness of the tube must be taken into consideration as well, when talking about safety. Network of tubes is new concept for transporting people, but in terms of transporting gas or industrial liquids, similar networks already exist, which means, lot of knowledge and experience exists about building these structures safely. Round structure itself being one of the strongest structures possible and can even resist earthquakes. Pressure difference between inside and outside is also nothing new, it is similar to what gas and oil pipes are experiencing.
(Kurstjens, et al., 2022).

Another notable detail is that according to Gresta (2022), tube cannot be damaged from the outside by gunfire, at it is made to withstand a strong explosion.
(Kurstjens et al., 2022).

Safety of the pod/capsule

Since the pods move through vacuum, leaving the vehicle in case of an emergency will work differently from, for example, a train. In the very unlikely event of an emergency due to technical failure, the pod will automatically come to a halt with a fast but safe deceleration rate of 1 G. If possible, the pod will move to a safe haven compartment that has exits in the tube that will allow passengers to leave the infrastructure in the same way passengers would disembark in a station. If it is not possible to reach a safe haven, the pod will stop inside the tube. This compartment of the tube will be sealed off and brought back to atmospheric pressure. Passengers can then leave the pod into the pressurized tube and walk to the nearest exit point. Via the interpod communication links, other pods will be notified of the stranded vehicle and, if possible, automatically find a detour around the pod via high speed lane switching. (Kurstjens et al., 2022).

Hyperloop Transportation Technologies have a slightly different approach to this. In their version of tube, gigantic recompression valves are placed every 10 kilometers. The place of emergency is isolated, valves are opened and air from outside enters the tube, which compensates for the deviation by taking advantage of the pressure difference. This recompression process is done within seconds. Gresta emphasizes that there is no risk of explosion for either the capsule or the tube. The pressure difference between the interior and exterior is minimal. To put into perspective, the difference is approximately galf of that between the inner tube of a bicycle and the surrounding air. As Gresta states, most of us have experienced a punctured tire at some point in our liver. The tire deflates but does not explode, despite being made of rubber. In the case of the hyperloop, we are dealin with and incredibly strong material to withstand various pressures.
(Gresta, 2022)

2.6 Emissions reduction

There is a pressing global need for a more sustainable approach to rapid transportation. To effectively reduce CO2 emissions, countries must make changes to how people travel medium to long distances. Currently available options, such as rail transport and airplanes, are either highly polluting or lacking in speed. It is projected that the demand for transportation will triple in the next 30 years (Kloth, 2019), and the transport sector is the second-largest emitter of greenhouse gases, accounting for 16.2% of all emissions (Ritchie et al., 2020).

Hyperloop could provide a solution. It offers operational speeds comparable to airplanes while consuming less energy than high-speed rail (HSR; Tayilor et al., 2016; Dabrowska et al., 2021). The hyperloop is designed to run on electrical energy, which can be generated from sustainable sources, thereby minimizing greenhouse gas and toxic emissions. In essence, the hyperloop combines the advantages of speed and sustainability, offering the best of both worlds.
(Kurstjens et al., 2022)

Report published by IPCC shows, that CO2 are the main cause of the climate change and reaching close to zero CO2 emission is the only chance to minimize climate impact. This speaks in favour of hyperloop again. Thankfully, the European Commission is already taking an increasingly stronger position, among others by including the hyperloop in the Smart and Sustainable Mobility Strategy action plan, as a crucial element in reducing transport emissions. However, more decisive course of action is necessary. (Hardt Hyperloop, 2021)

After implementation of hyperloop transport system, CO2 emission will be reduced by 143 million tons per year, according to HTT analysts' estimation.

(It's not logistics fiction: this is how Hyperloop will be used in ports, 2022)

3. CURRENT STATUS OF DEVELOPMENT

3.1.1 Hyperloop Transportation Technologies

Shortly after Musk's document was released, many companies wanted to join the hype, and create functional Hyperloop based on Elon Musk's vision. Probably first company to start development was *Hyperloop Transportation Technologies*, founded by JumpStarter, Inc. in 2013 (Chang, 2013). Hyperloop Transportation Technologies is a company with hundreds of engineers with day jobs in companies like Boeing, NASA, SpaceX, Tesla, Boeing and Lockheed Martin (Gresta, 2022). They began constructing the test track in 2016, and their aim for the train is to reach speed of 760 mph (Garfield, 2018). Originally, aim was to have working system used by passengers by 2018. The company made agreements with multiple countries, such as China, Slovakia, Saudi Arabia, India to perform their studies and built tracks. Currently, the company is designing four prototypes, in France, Abu Dhabi, Ohio and Hamburg. French track is 4 meters in diameter, which was making it only full-scale hyperloop test track at the time of construction (Cooper, 2018). The track is approximately 300 meters long. According to Gresta (2022) in his publication, HTT had significant advantage during construction of the test track, because the levitation system they used, called Inductrack (briefly explained in chapter 2.3.2) was already established. The company already revealed 2 different prototypes of capsuled. Second capsule was released recently, at MWC in Barcelona, in February 2023 (De Madrid a Barcelona en menos de una hora: así es el tren que conectaría

Fig. 9 - Hyperloop Transportation Technologies' first full-scale capsule, the Quintero One (Houska, 2018)

ambas ciudades a 1.200 km/h, 2023). With capacity of $32m^2$, inside which 28-58 people would fit, as explained by CEO Andrés de León. Capsule is made of 82% carbon fibre.

3.1.2 The Boring Company

Another company is The Boring Company. Company was founded by Elon Musk in 2016. They already developed a test tunnel in California for public transportation systems in 2018 (Lavrence, 2021). In early 2022, they announced that they will begin with tests before the end of the year (Korosec, 2022). Company shared pictures on social media with their new test tunnel, apparently in Texas with new facility for their tests, with description that tests are beginning (Lambert, 2022). Even though, there has not been any tests reports, they are probably already doing first steps towards successful tests so it can happen soon. As I already mentioned, company was founded by Elon Musk together with SpaceX. Their minimalized test tunnel was lately disassembled, meaning that activities around Hyperloop are probably being moved under the heads of The Boring Company. (Melechin, 2022)

3.1.3 Nevomo

Nevomo, a Polish company, known as Hyper Poland until 2020, is making their approach too. They approach is based on Maglev train technology. They call it MagRail (Klos, 2020). Their first prototype was built by a student team, later on, the company won multiple awards and also created an international team. Nevomo is supported by big

Fig. 10 - Future visualization (Sůra, 2022)

partners such as Microsoft and WUT. Company was initiated in 2015 based on student's thoughts and academic researches, and scientists representing WUT (Klos, 2020). Their approach by implementing MagRail is, as they said, "More down to Earth". MagRail is a levitation train, which is operational on already existing railway tracks, which can be later transformed into vacuum train (Klos, 2020).

Nevomo began technology development with this hybrid solution because development of hyperloop is complicated and expensive, so they want to use concepts of hyperloop and combine them with existing railway tracks. In words of co-founder Kasia Foljanty: "The main idea behind the design and the development of the MagRail technology was to use the existing rail infrastructure and turn it into a much more efficient and effective transportation system, while allowing conventional trains to use the same tracks in a conventional way". According to Nevomo, MagRail will allow transportation at double the average speed of a conventional railroad – 550 kilometres an hour. MagRail utilizes passive magnetic levitation to achieve vehicle levitation through automatic means once the vehicle reaches a certain speed. Propulsion for the vehicle is facilitated by a linear motor placed in the middle of the rail track. Unfortunately, the company has not given any more detailed info about how MagLev would work and how it would be implemented.
(Geerts, 2022)

Their aim is to have a functional system, operating at 1200 km/h. The company already carried out successful tests on medium-sized line in 2021 (Rail Target, 2021). Apparently, in early 2022, they finished their first test track for levitation trains in city of Nowa Sarzyna, which is their first step, to evaluate their technology (Sůra, 2022; Nevomo, 2022b). At the beginning of September 2022, first prototype arrived at this new test track. (Nevomo, 2022b)

3.1.4 Hardt Hyperloop

The winner of the SpaceX's hyperloop competition in 2017 was Hardt Hyperloop, a company based in The Netherlands (Lavrence, 2017). They built their own test facility in 2019, where they carry out test with every component of Hyperloop, in full scale. This company likes to call themselves "The First European Hyperloop". They have slightly different approach than other companies. The company is working on connection of tubes which functions like highways, meaning one can go off the particular track and join another. Hardt plans to build their own 10-15 kilometres long test route built by 2023 and want to operate commercial lines by 2028, which is very ambitious. Their vision is to connect every major European city by hyperloop. (Hardt Hyperloop, 2019) As of 2023, they say that all of existing and new technologies needed for hyperloop are proven at their Low Speed Test Facility and are prepared to test them in Groningen at the European Hyperloop Center this year. Their ambition now is to realize first commercial route before 2030, with dozens of routes being prepared and planned at the same time, to get ready for implementation before 2040.

3.1.5 Hyperloop One

Another company that wanted to join the hype around Hyperloop concept was Hyperloop Technologies, later known as Virgin Hyperloop One (currently known as Hyperloop One) founded by Shervin Pishevar and Brogan BamBrogan. As of now, it is the company which arguably came closest, to a functional Hyperloop system. Hyperloop One built an open test track in Nevada, where they, according to The Guardian, carried out a Propulsion Open-Air Test in May 2016 (Woolf, 2016). Even thought, the test did not take place in a vacuum tube, it was a success. Test sled did accelerate from 0 to 100 mph in just one second (Alba, 2017). Shortly after that, fabrication facility was opened in Las Vegas, which was set for the production of a full Hyperloop test track.

The test track was named DevLoop (Alba, 2017), it was the place of the very first full system Hyperloop demonstration, on May 12, 2017. The test appeared to be successful. Pod named XP-1 was accelerated to speed of 70 mph in the low-pressure tube.

Fig. 11 - Pod of Hyperloop One - XP-1 (Walter, 2020)

That confirmed that all prototype components are working (Macola, 2021; Alba 2017; Garfield 2018). Pishevar said “Hyperloop One has accomplished what no one has done before by successfully testing the first full scale hyperloop system. By achieving full vacuum, we essentially invented our ‘own sky in a tube’, as if you're flying at 200,000 feet in the air. For the first time in over 100 years, a new mode of transportation has been introduced. Hyperloop is real, and it's here now.” (PRNews wire, 2017) On July 29, 2017, another test was carried out by Hyperloop One, in which their pod reached speed of 310kmh during the test, then fastest recorded speed of any hyperloop test (Etherington, 2017). In October 2020, Hyperloop One successfully carried out their first passenger test, and up to now, is still the only company to successfully carry out manned test. (Macola, 2021). In February 2022, company announced that they are shifting their focus away from transporting people, and will focus on transporting cargo (Paleja, 2022).

3.1.6 China and Korea

Researchers from the Chinese Academy of Sciences proposed their idea in 2017. Their idea is practically same, but they want to build hyperloop underwater. They propose that their pneumatic underwater train would run at a theoretical speed of 1240 mph, which is twice the speed of Musk's Hyperloop concept (Yue, 2017). On October 21st, 2022, China claimed that they successfully tested hyperloop-style train, on test track 2 kilometres long. Media are reporting that train reached speed of 80 miles, but theoretically can come close to speed of mach 1, once the design is completed. Chinese scientists are now working on construction of a full scale 60km test track, to test trains at 1000 km an hour (Dunhil, 2022).

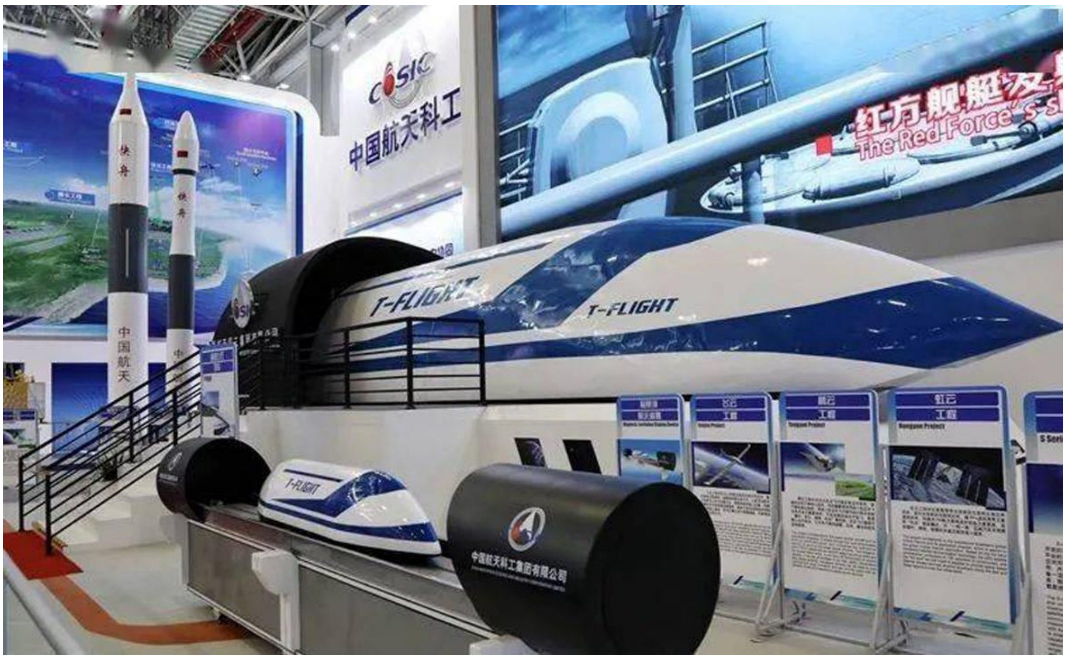

Fig. 12 - Chinese hyperloop pod (Dunhill, 2022)

In January 2023, China claimed that they successfully tested full scale passenger capsule, at a superconducting maglev test line in Datong. Tests were done by China Aerospace Science and Industry Corporation (CASIC). According to CASIC, all components including AI safety controls worked as they should during testing (Ouz, 2023). According to various media reports, China is likely to build their first line between Shanghai and Hangzhou, with the anticipated length of 150 kilometers. The whole process is on the right track according to nation's top engineering and rail design institutes. Line is expected to be operational by 2035. (China announces plans for world's first hyperloop line with 1,000 km/h trains, 2023)

In South Korea, The Korean Railroad Research Institute (KORAIL) reportedly achieved a speed over 1000 km/h during a test in 2020. Test was conducted on a scaled-down model at a 1:17 ratio. Their test track is 60 meters in length and is divided into three sections: accelerating, cruising and braking. The cruising segment is 20 meters in length and calculation of speed was performed using multiple fiber optic sensors. (A Step Closer to Near-Supersonic Train Travel, 2021)

3.1.7 Hyperloop Development Program

Hyperloop Development Program is public-private partnership of public sector, composed from research institutions, industry parties with common aim, to develop hyperloop. They are building their own testing facility called The European Hyperloop Center (EHC) in Dutch province of Groningen, which will be open testing facility for developers. More than 20 partners are included, such as Nevomo, Delft Hyperloop, Hardt Hyperloop, which I talk about in this paper.

The Program has three following goals for next 3 years:

1) To establish the viability of hyperloop as a secure and environmentally friendly mode of transportation for both individuals and goods.
2) To conduct tests and demonstrate in the EHC Groningen that the technology functions as planned and can be operated utmost safely.
3) The goal is to recognize the potential future possibilities and advantages for the industry and stakeholders involved in the hyperloop ecosystem.

Test facility which is currently under development is set to open in 2023. Developers from all over the world will be allowed to test and validate their technologies, in addition, it will serve as a research site. As stated on Hyperloop Development Program official site, it will be „A place where companies and research institutions can work together to accelerate the realization of the hyperloop.“ Testing facility will have 2,6 kilometres long test tube, split into 3 sections, consisting of booster section where the vehicle will be accelerated, test section, where tube splits into 2, so that a switch lane technology can be tested, and a braking section. In 2022 EHC and HUSA Logistics signed an agreement for construction of the hyperloop test center in Veendam. Construction of 420 meters long test track will begin in 2023 and should be opened in the second half of 2023. Then, this part will be reused in the 2,6km test track in Groningen.

(Hyperloop Development Program, nd.-a; Hyperloop Development Program, nd.-b)

3.2 Cost

The cost is overall being considered as the biggest setback, because the whole infrastructure has to be developed, manufactured, built, and maintained. The capital expenses associated with the hyperloop guideway display a significant reliance on the particular propulsion technology selected for the hyperloop system. Two propulsion systems, LSM and LIM, as mentioned, are deemed suitable for the hyperloop. Utilizing the LSM involves incorporating active components within the track, which consequently leads to greater capital costs compared to employing the LIM. This is due to the necessity of integrating these active components across hundreds of kilometres of track. However, it is important to acknowledge that the LSM offers enhanced energy efficiency, thereby resulting in reduced expenditures associated with energy consumption.

Cost assumptions differ from different parties. Starting at 13.3 million dollars per kilometre (Musk, 2013) to 56.4 million dollar per kilometre (AECOM, 2020). Difference is made by elements that were and were not considered. Some studies include station costs, placement of the tube also projects into final cost, because putting tube underground requires tunnels, and boring technologies are at the moment one of the most expensive in existence (Gresta, 2022). Number of pods being made is another factor which differs in different studies. As to maintenance costs, Delft Hyperloop assumes the maintenance cost to be 50,000 – 150,000 euro/km/year for an above ground tube and 210,000 - 370,000 euro/km/year for an underground tube. Lastly, it is important to acknowledge that infrastructure cost predictions often prove to be inaccurate, with a significant proportion of projects underestimating their total expenses. Empirical research conducted by Day and Harvey-Rice (n.d.) indicates that approximately 45% of rail projects surpass their initial budget estimates. This finding raises concerns regarding the current cost projections for hyperloop infrastructure, suggesting that they are likely to be underestimated. To illustrate, consider the case of the HSL-Zuid high-speed rail line connecting Amsterdam Schiphol Airport and Antwerpen. Originally projected to cost 3.4 billion euro in 1997, an evaluation conducted in 2015 revealed that the project ultimately incurred a total expenditure of 7.3 billion euro upon completion (De Pater et al., 2020). (Kurstjens et al., 2022)

3.3 Demand

The demand for any mode of transportation is influenced by a range of factors, including the demographics and economics of a city, ticket prices, travel time savings, reliability, comfort, and the accessibility of transportation stations (Victoria Transport Policy Institute, 2015). The hyperloop system is no exception to these considerations. Consequently, the placement of hyperloop routes assumes crucial significance, as connected cities must possess the capability to meet the demand necessary for the system's feasibility, which is contingent upon city population and economic factors. Various groups of travelers will utilize the hyperloop for different purposes, such as work-related trips, recreational activities, visiting family, or commuting to school. Each group places differing values on various aspects of the transportation experience. For instance, daily commuters prioritize ticket prices and reliability, while business travelers prioritize time efficiency. Given these considerations, it is anticipated that densely populated cities would readily meet the demand required for the viability of hyperloop operations.

Research indicates that the average one-way daily commuting time in Europe was 25 minutes in 2019, with 26.3% of the working population traveling between 30 and 59 minutes (Eurostat, 2020). Moreover, commuting times have increased over the years, with a 10% growth in average commuting times in the United States between 2006 and 2019 (United States Census Bureau, 2021). With the hyperloop's ability to offer short travel times, such as a journey of approximately 30 minutes from Amsterdam to Paris, the hyperloop could potentially become an integral part of people's daily commute. (Kurstjens et al., 2022)

Hyperloop is supposed to be very easy to access, because it is planned to have hyperloop linked into already existing infrastructure, with the stations, which are often called *portals*, placed in the city areas, which is big advantage over travelling in airplanes. Like train stations, hyperloop stations, are planned to be located within inner city areas with easy links to existing transport infrastructure, as Cortese (2018) stated in his article. This would give hyperloop systems a distinct advantage over air travel since airports are often located outside of the city. However, implementation of hyperloop will require building of entirely or at least partially new infrastructure. Kurstjens, et al. (2022b) says, that much more information is required before implementing first hyperloop corridor. No company has shared detailed information about linking hyperloop infrastructure with already existing infrastructure.

4. POSSIBLE FUTURE DEVELOPMENTS

4.1 Problems yet to be solved

For hyperloop to be implemented, number of different problems must be solved. Gravitational forces are one of them. G-forces during the acceleration and deceleration are not the problem, but G-forces during turns could be causing problems, but they are solvable. Commercial jets fly at speeds exceeding 800 kilometres an hour, they make turns, climb, experience turbulence, and the whole system is efficient, which proves that staying at high speeds while making a turn is achievable. The big difference is – airplanes fly, hyperloop will be on, above or under ground. Smooth and straight path will be needed and will require large amount of work. However, this objective has also been achieved with implementation of The Eisenhower interstate system, with length of almost 80 thousands of kilometres.

However, major problem is one of the basics of the whole hyperloop idea – vacuum. As mentioned before, vacuum or near vacuum environment is technically difficult. And building giant tube with enough integrity is similarly challenging. It is no question that to ensure structural durability, tube cannot be made of transparent materials, as seen on some marketing materials, but rather from steel or concrete. Welded steel would offer significant resistance to air leaks, but the thermal expansion and contraction of the massive structure would necessitate substantial engineering effort to enable unrestricted movement. Alternatively, if the system consists of many small steel tubes connected through joints, those joints must be capable of maintaining the vacuum's integrity, Perfect engineering is critical, as even a single joint failure could have catastrophic consequences (Hartsfield, 2022). Solution with small tubes is used at HTT as mentioned by Gresta (2022). To accommodate thermal expansion, the pipeline incorporates specially designed accordion expansion joints positioned strategically throughout the route. This arrangement allows for the pipe to elongate and contract in response to the material's expansion and contraction during day and night cycles while maintaining perfect alignment.

Another problem, related to vacuum environment is the design of the platform sections. Because of the environment inside the tube, pressurising systems must be implemented. Delft Hyperloop shares three options. One consisting of bridge door concept, where the pod remains in the vacuum, and passenger will commute between pod and station through a bridge which is being pressurized and depressurized. The second alternative presented is the utilization of an airlock chamber, where pressurization or depressurization takes place in order to allow the pod to enter the station at atmospheric pressure. This approach is supposed to be more economically viable, its setback is in duration of the operational process, which contradicts with objective of the hyperloop project. The third option is end-door airlock, where the pod remains in the vacuum environment an establishes connection with the station through a sealed connection. This is yet another challenge, that must be overcome during the initial stages of implementation. (Gerritse & Xanthopoulos, 2021)

Delft Hyperloop states in their report, as many others, technological side of the hyperloop is not the biggest challenge. The biggest challenge of hyperloop, in terms of implementation, according to report done by Kurstjens, et al. (2022) for Delft Hyperloop in 2022, lies in social and economic aspects, as well as in decisions of investors and stakeholders. Variety of stakeholders is involved in the development of a European Hyperloop network, which is positive, because of the price of Hyperloop ticket. The ticket price has to cover all the costs, such as operational costs, maintenance, capital, and on the other hand, has to compete with costs of already known transport, meaning planes, trains, et cetera. Capital is obviously going to be a high number, because even if the cost per kilometres is not much higher than other modes of transportation, network with length of hundreds of kilometres needs to be made.

Another barrier in terms of implementation is standardization. Various companies are currently developing different propulsion systems and utilizing different levitation technologies. This may result in a problem, that pods from company A may not be compatible with company's B track, and that would create a problem, that pod could not travel from one country to another. Regarding standardization, Delft says, that hyperloop needs at least European standard if not an international one. Talking about standards, Delft also states, that safety standards with level at least as high as aviation safety standard need to be set, because of high operational speeds hyperloop is aiming to achieve. Institution for setting these standards has to be found. Within the European Union (EU), distinct safety agencies exist for various modes of transportation, responsible for developing safety standards and requirements applicable to transportation systems within the EU. For instance, the European Railway Agency (ERA) assumes the role of safeguarding safety standards specific to European railways (European Commission, n.d.). It may also be plausible to designate an independent safety agency to effectively fulfil this responsibility.

In addition to safety standards, standardized operations for the hyperloop are crucial. To establish the hyperloop as a consistent and integrated transportation network, it is crucial to ensure uniformity in station procedures and operations, irrespective of the country in which stations are situated within the hyperloop network. Each station should uphold a consistent level of security and service quality.

4.2 Projects under development

There are lot of undergoing projects at the moment. Number of different companies are working at their concepts and testing tracks. TransPod, a Canadian company founded in 2015 has announced new phase of their project in Alberta, Canada. Broughton Capital Group and China-East Resources Import & Export Co. agreed in cooperation and provided 550 million dollars to accelerate development of TransPod line between Edmonton and Calgary. Feasibility study states, that the project will create 140 thousands jobs and will add 19.2 billion dollars to regions GDP during construction (by 2030). Construction of track should begin in 2027. Route from Calgary to Edmonton should take 45 minutes at approximately 72 dollars per ticket. Driving from Calgary to Edmonton takes more than three hours, plane ticket cost 129 dollars. This line is expected to reduce CO2 emissions by 636 000 tons per year, or equivalent of planting a forest four times bigger than Calgary (which is 825 km^2 big).
(TransPod moves forward with ultra-high-speed tube transportation in Canada, 2022)

During February 2023, information about new possible project in Spain started to appear on the internet. According to Euro Weekly as written in article by King (2023), Hyperloop Transportations Technologies wants to connect Madrid and Barcelona, and estimates, that Madrid-Barcelona trip will cost around 75 per cent of plane ticket cost, and estimated payback period being 15 to 25 years, according to calculation in their studies. Furthermore, CEO of Hyperloop Transportations Technologies Andrés de Leon states, that a project in Italy is currently under development. Aim is to build 10 kilometres long tube between Venice and Padua (By train Hyperloop within half an hour from Madrin to Barcelona, 2023).

On March 10th, 2023, a cooperation agreement was signed in Paris between SNFC and Nevomo. SNFC, France’s national state-owned railway company signed a Memorandum of Understanding to „to evaluate the benefits of MagRail within French railway network to increase the efficiency and capacity in passenger and freight transport and therefore support SNCF’s strategy.“

As SNFC’s Innovation director Luc Laroche said, SNFC noticed that Nevomo’s proposed technologies can possibly help the railway. This Memorandum of Understanding covers 3 areas: Increasing the performance of current freight trains for higher loading limits and more capacity on our freight lines, boosting the capacity on congested urban passenger lines, and evaluating MagRail as an alternative propulsion system for rural lines in combination with lightweight vehicles. (Nevomo, 2023)

When considering the implementation of the hyperloop, many may immediately think of the potential line connecting Abu Dhabi and Dubai. However, surprisingly, the construction of this line is unlikely to occur in the near future. Although Dubai may be open to the idea, it can be said that Abu Dhabi has different priorities at the moment. The government of Abu Dhabi, which primarily relies on oil as its main source of revenue, is the wealthier emirate between the two. In recent decades, Abu Dhabi has often assumed financial responsibility for the ambitious visionary projects of Dubai, which, in contrast, relies heavily on tourism. The Sheikh of Abu Dhabi aims to transition his country away from dependence on the oil economy and therefore prioritizes investments in projects that yield immediate positive impacts on the city. Establishing a hyperloop line between the two cities, which are currently 145 kilometers apart, would incentivize people to reside in Dubai, which offers superior amenities and entertainment options, as well as a lower cost of living. As a result, the preferred option at present is to develop a line connecting Abu Dhabi and Al Ain. (Gresta, 2022).

Proposed routes:

Fig. 13 - Planned routes for America (Hardt Hyperloop, 2022a).

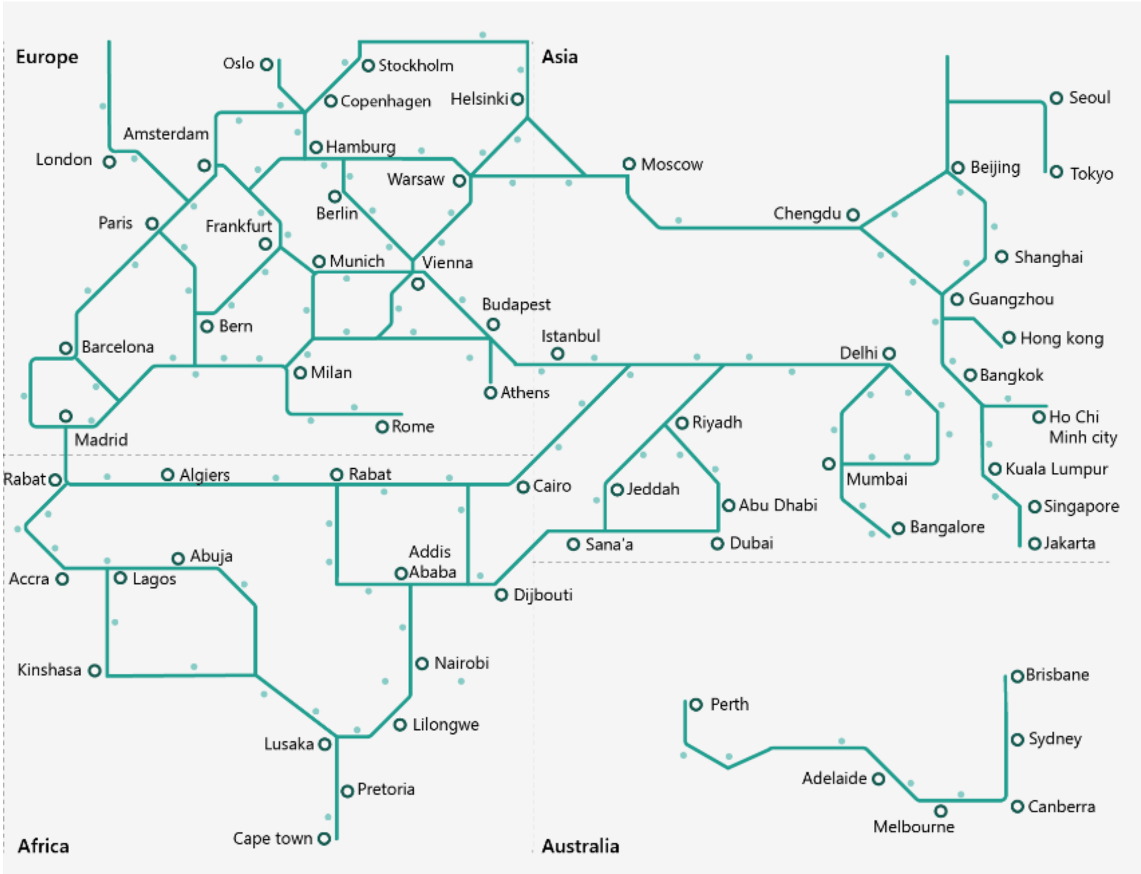

Fig. 14 - Planned routes for Africa, Australia and Europe (Hardt Hyperloop, 2022a).

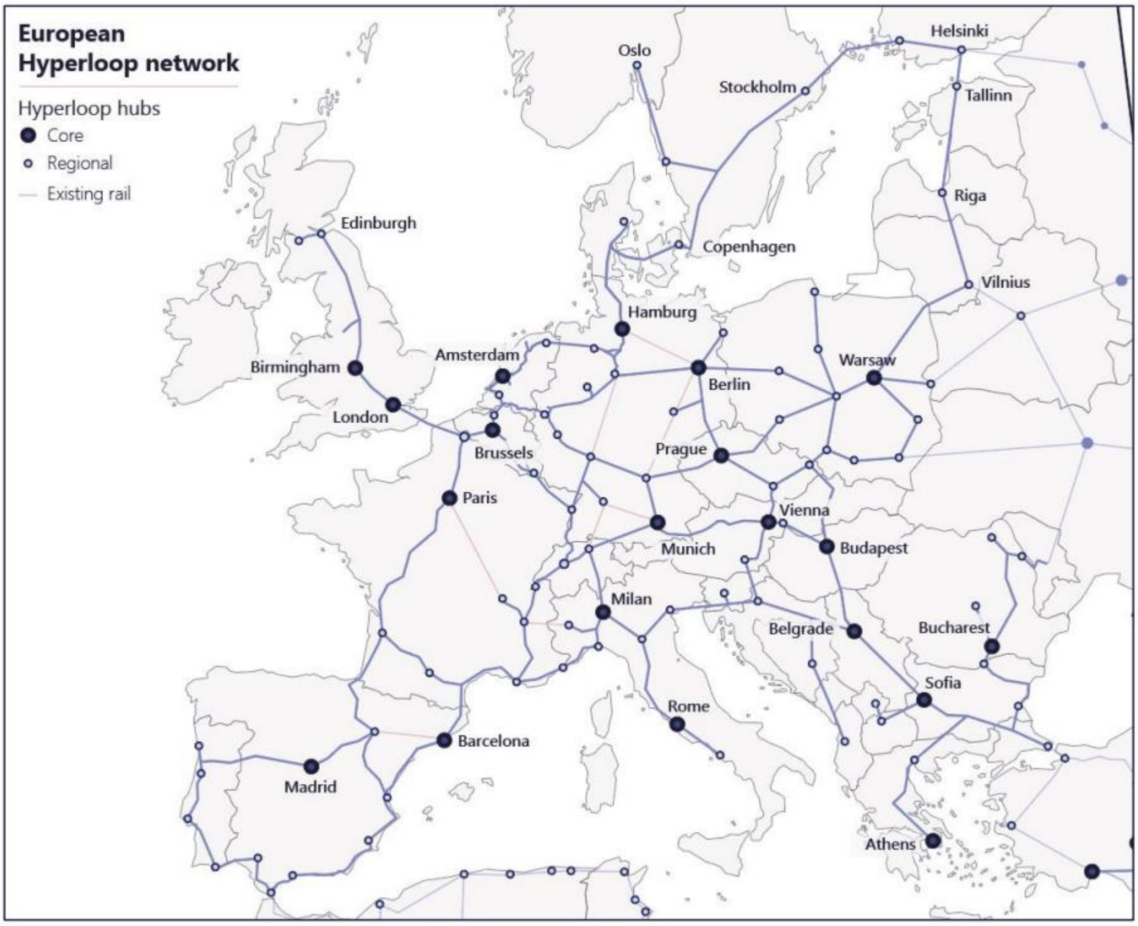

Fig. 15 - Planned routes for Europe (Hyperloop Development Program, 2022).

4.3 The future

A common misconception about the hyperloop is that the hyperloop will completely replace aviation or high-speed rail. Given the characteristics of the system, this is not possible. With the demand for travel predicted to almost triple by 2050 (Gössling and Humpe, 2020), it will also be difficult even for aviation and rail to provide sufficient capacity for this demand. It is already expected that aviation will face capacity challenges (Supporting European Aviation, 2018). When the hyperloop will be developed is a question which is not easy to answer. Students working on Delft Hyperloop are proposing, that first implementation of hyperloop in Netherlands can be done in 15 years. (Rail, 2022)

The future of hyperloop implementation is an exciting prospect that holds great potential for revolutionizing the way we travel. With several companies actively working on the development of the hyperloop system and proposals for routes emerging around the world, the possibilities are big. The technological advances that hyperloop offers make it an even more attractive option for long-distance travel, offering reduced travel times and enhanced sustainability. However, there are several challenges to consider, which I have already mentioned. In addition, it will be essential to ensure that this new mode of transport is accepted by the public and embraced. In addition, cooperation between governments will play a crucial role in shaping the future of the hyperloop. The proposed routes stretch across continents, with a vision of connecting megacities and high-density corridors. These routes are carefully planned, taking into account factors such as population density, travel demand and geographical feasibility. By pushing the boundaries of technology and creating an interconnected network of hyperloop routes, we could see a future where travel is transformed and connects people and places like never before.

5. CONCLUSION

This research paper aims to provide an exploration of the historical development of the hyperloop transportation system, tracing its evolution from its first concepts to the latest prototypes. Historical section mentioned key milestones that have significant importance.

In the part “Technological concept”, infrastructure of hyperloop and some of the technologies used in this futuristic concept are explained briefly. Due to fact, that the whole technology is in many ways just a theoretical concept, and the great technical difficulty of it is making the topic very comprehensive for this bachelor’s, details of some technical features are not mentioned.

I find it important to acknowledge the difficulty of finding comprehensive technological information due to absence of any functional system anywhere in the world as of the time of writing (May 2023). Therefore, finding detailed technical information is extremely demanding, and in some cases, almost impossible, hence, to gather the necessary information, I relied on fragmented sources such as companies’ websites, publicly available documents, article, and studies. Additionally, I made a choice to rely on a single book that proved to be adequate in addressing the research requirements.

After briefly describing the technology used, number of safety features are presented. Subsequently, an analysis of cost assumptions is provided, along with summary of ongoing projects and outline of possible future development.

Biggest benefit of hyperloop is undoubtedly its speed. If hyperloop will become fifth mode of transportation and will live up to visions different companies are proposing, travel time between cities or parts of the country will be dramatically reduced, that being said, it will be much easier to get to the place you are working at, even if it is in different part of the country. Due to this fact, hyperloop itself holds the potential to emerge as a transformative mode of transportation in the future. Considering the rise of global population and the increasing demands for efficient travel solutions, it is a matter of time before the hyperloop or something else becomes an integral part of our daily lives. Based on information I was able to gather during this comprehensive research, about different aspects of hyperloop, it is important to say that hyperloop is not a mirage. However, based on relatively slow progression of different companies, some additional time is needed before the implementation of this revolutionary transport system can be realized. Number of different challenges have to be yet overcome. Some people are skeptical about hyperloop, saying it will never happen and that it is impossible. However, my perspective differs from those individuals. Given the fact, that the fastest plane in the world was built almost 60 years ago, building hyperloop should be possible, but maybe even several decades will pass, until its global implementation becomes a reality.

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Symbols and abbreviations

Abbreviations:

AI	artificial intelligence
CASIC	China Aerospace Science and Industry Corporation
CEO	Chief executive officer
CO_2	carbon dioxide
GDP	gross domestic product
G-force	gravitational force
EHC	European Hyperloop Center
HTT	Hyperloop Transportation Technologies
IPPC	Integrated Pollution Prevention and Control
Km/h	kilometers per hour
KORAIL	The Korean Railroad Research Institute
LIM	linear induction motor
LSM	linear synchronous motor
MagLev	magnetic levitation
MIT	Massachusetts Institute of Technology
Mph	miles per hour
MWC	Mobile World Congress
SNFC	Société nationale des chemins de fer français
WUT	Warsaw University of Technology
XP-1	experimental pod 1
XP-2	experimental pod 2

Symbols:

MW	power	(W)
Wh	watt-hour	(-)