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# Hyperloop: a breakthrough for vacuum transportation?

## Technology analysis and evaluation of commercial prospects

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## Executive summary

Emissions from the transport sector accounted for over 24% of global $CO2$ emissions in 2016 and continue to rise quickly mainly due to the rapid growth of air traffic.[1] Because of this, there is an urgent need for more sustainable transport infrastructures in order to reduce emissions and achieve global climate targets.

Vacuum transportation could serve as just such a sustainable transport option. In recent years, Elon Musk has revived interest in vacuum transport with his Hyperloop Alpha paper in 2013 along with his SpaceX pod competitions. Hyperloop is a variant of vacuum transportation systems that aim to propel passengers and/or cargo through low-pressure tubes above or below ground, thus reducing friction and aerodynamic drag. As a result, hyperloop and other vacuum train (vactrain) variants promise high-speed transportation with reduced energy consumption.

**Technological challenges appear solvable**
Many of the core technologies of vacuum transport such as magnetic levitation are well-developed and have been tried and tested in applications such as the Transrapid. However, the combination of maglev technology with vacuum tubes over long distances still requires extensive testing before the best technological combinations will be discovered, the remaining technological challenges will be overcome, and commercial tracks will become feasible. Many corporations and research institutions around the globe are currently working on this issue. The construction of test tracks will play a crucial part in further advancing the technological readiness of vacuum transportation. It is difficult to forecast a precise date, but in our view, it seems realistic that hyperloop/vactrains will be ready, technologically, within the next 10 years.

**Vacuum transport offers advantages, but costs are a major obstacle**
Technological readiness is not sufficient for commercial implementation though. Hyperloop/vactrains also need to offer clear advantages over existing transport means. Vacuum transportation provides certain benefits such as higher speeds and a better energy-efficiency. The speed advantage appears to be particularly attractive for medium distances (between approximately 300 km and 1,400 km) because factors such as access and egress time reduce the speed advantage for shorter distances. However, the cost reductions compared to high-speed trains that are promised by several hyperloop companies seem unattainable. Even though advances in passive maglev will possibly reduce costs, the construction of vacuum tubes will remain a primary driver of costs. Costs will be particularly high in mountainous areas that require extensive tunneling such as in Switzerland. Construction costs are also the reason why very long travel distances between two hubs seem less attractive for hyperloop/vactrains.

**First commercial tracks will likely be built in Asia**
The best prospects for the construction of the first commercial vacuum transportation tracks appear to be in areas where there are no geographical obstacles and where there is not already an established, extensive system of transportation infrastructure. Moreover, political support is important as the construction of the first commercial

[1] https://www.wri.org/blog/2019/10/everything-you-need-know-about-fastest-growing-source-global-emissions-transport

tracks requires significant public spending and carries obvious risks - such as budget overruns - due to the novelty of the technology.

We see the highest probability of completion of the first tracks in the Middle East, India, and China. In Europe and Switzerland, a reduction in tunneling costs would be necessary before hyperloop/vactrains could become a competitive transport option. However, there are also some characteristics in Europe that might lead to the adoption of vacuum transportation in the region at a later stage if the initial projects in Asia turn out to be successful and tunneling costs decrease. For example, climate targets in the EU are more ambitious than in most other regions and, thus, the pressure to implement more energy-efficient transport options is higher.

**China has the most patents, but Virgin Hyperloop One has the highest rated portfolio**
Patent data was analyzed to determine which countries, companies and universities are in the lead concerning intellectual property rights in vactrain/hyperloop technologies. Two technology fields were created with the Swiss Federal Institute of Intellectual Property for this purpose – a narrow definition of patents specifically for vacuum transport and a broad definition covering related technologies. The focus was not only on the number of patents, but the quality of patents has been considered as well.

China holds the most patents both in the broad and narrow technology definition. Chinese universities such as Chinese Southwest Jiaotong University and state-led companies such as China Railway Construction and the Chinese CRRC Group have large patent portfolios in these fields. However, the average valuation score of Chinese patents is significantly lower than the scores in the US or in Europe.

In the broader technology definition, the US and the European countries are on relatively equal footing in terms of patent numbers and scores. There are also many patents from Japan and South Korea, but their average patent score is lower. Industrial companies such as Rockwell Automation, Siemens, or ABB hold many patents. ABB has patents in related technologies such as linear motors and is, therefore, in a good position to become a major technology supplier for vacuum transport in the future.

In the narrower technology definition, the number of patents is still relatively small, which indicates that vacuum transport is in the early stages of development. On a patent owner level, Virgin Hyperloop One (VHO) has the highest-rated patent portfolio.

**Swiss universities are among the leading research universities in vacuum transport**
Since not all new inventions are patented, it is also important to consider further information sources. The results from a media analysis by LinkAlong show that hyperloop has been a frequent topic in press articles and scientific publications in recent years.

On a company level, Virgin Hyperloop One and Hyperloop Transport Technologies dominate the press coverage. Virgin Hyperloop One is also the leader in terms of articles where hyperloop companies and established industrial companies are cited together. This is an indicator that Virgin Hyperloop One has partnered with many companies.

Most universities that have been in the media related to hyperloop were participants in the SpaceX hyperloop pod competitions in 2018 and 2019. The Indian IIT Madras, the Delft University of Technology, and the Technical University of Munich reached the top three spots, the EPFL was close behind in fourth place and the ETH was just barely outside the top 10. In addition, both EPFL and ETH achieved very good results in the aforementioned pod competitions. These results show that Switzerland is among the top countries in terms of university research in hyperloop.

**Most experts see commercial prospects for vacuum transport, but mainly in Asia**
In addition to the patent and media analyses, six interviews with transport experts from universities, companies, and consultancies were conducted to discuss the prospects of vacuum transport. Most experts agreed with our assessment that the technological challenges can be solved within the next 10 years and that the main obstacles are the high costs for the construction of the tubes and tunnels. Given this, most interviewees predicted that the first commercial tracks will likely be built in the Middle East or Asia. Regarding the commercial prospects for Switzerland, the interviewees stated that many Swiss companies are in a good position to become suppliers of technology for hyperloop/vactrain tracks in various fields such as power electronics or vacuum tech.

However, there are also differing assessments. For example, some experts think that safety issues related to the required vacuum are a key problem, whereas other experts are convinced that vacuum technology for the tubes/tunnels is already well-developed and all safety issues can soon be solved. There are also differing assessments regarding the impact of vacuum transportation on greenhouse gas emissions. Several experts expect that the implementation of hyperloop/vactrains would reduce greenhouse gas emissions thanks to its higher energy efficiency. However, two experts argue it would lead to a rise in induced demand for transportation and this effect could, in turn, possibly undo any reduction of emissions.

Finally, one expert predicted that a commercial vacuum transportation track in Switzerland will be built in around 20 years. Other experts thought it would take at least 40 years before a commercial track in Switzerland becomes realistic and one expert is convinced that commercial tracks will never be built in Switzerland.

**The Eurotube research center – a high risk, high reward project**
In Switzerland, EuroTube plans to build a publicly accessible research center including test tracks in the canton of Valais.[2] As a non-profit research organization, the EuroTube Foundation depends on funding and donations and has requested public funding from the federal government in order to build its first test track.

The EuroTube research project could generate significant value in Switzerland if its research site succeeds and becomes a leading global research cluster. A technology cluster could lay the foundation for a new industry that would establish numerous high-skilled jobs in Switzerland, lead to the emergence of new businesses, build national and international networks, and create significant knowledge spillovers. A promising aspect of having a vacuum transport research center located in Switzerland is that there are already several Swiss companies that are active in relevant technologies such as power electronics and energy solutions (ABB), sensors (Baumer), vacuum technology (VAT Group), or tube materials (Creabeton).

Even though the first commercial tracks will likely be built in Asia, Swiss companies could benefit from this by becoming suppliers of technology. In this way, Swiss

[2] https://eurotube.org/about-us/

companies and start-ups could capitalize on the knowledge and expertise they gain during the testing phase even if they don't build tracks in Switzerland.

That said, there will be tough competition between different research sites in the coming years. However, given the excellent research capabilities of Swiss universities in vacuum transport technologies and the numerous Swiss companies actively working on other relevant technologies, EuroTube is in a good starting position and possibly even has a competitive edge on its competitors. Despite this, it is not guaranteed that EuroTube can, in the long run, keep up with its rivals from the US, Asia, and Europe.

All in all, the EuroTube research project is, therefore, a high-risk, high-reward project. Given the relatively manageable amount of public funding that is needed to initiate the construction of its first test track, we think that it is the right decision to publicly fund EuroTube in order to boost the chances of bringing the testing and further development of hyperloop/vactrains to Switzerland. However, it will be important in the coming years to closely monitor the progress of the technology developed in Switzerland and to compare that progress with its competitors.

# 1 Introduction

Hyperloop refers to a new transportation system intended to supplement existing (passenger) transportation infrastructure. It describes transportation through low-pressure tubes using levitated capsules propelled by electric/magnetic propulsion. Hyperloop aims to provide high-speed transportation with reduced energy consumption. The commercialization of hyperloop technology could have a substantial impact on transportation systems. It could represent a fifth mode of transport which goes beyond our existing modes of transport: boats, planes, cars, and trains.

A crucial advantage of hyperloop is its potential to reduce energy consumption and CO2 emissions while increasing travel speeds compared to the high-speed trains or commercial airplanes of today. Transport emissions accounted for over 24% of global CO2 emissions in 2016 and emissions are rising faster than in other sectors mainly due to the fast growth of air traffic.

In realizing this concept, several different solutions are possible, each with different technical, operational, and commercial properties. Although hyperloop incorporates vacuum train concepts like that of Swissmetro, which have been around for many years, the development of the technology for hyperloop/vactrains remains in its experimental stages. Indeed, several technological challenges need to be addressed before commercial tracks can be built. Several corporations and research institutions around the globe are currently working on R&D and feasibility tests. In Switzerland, the non-profit organization EuroTube plans to build a publicly accessible research center including test tracks in the canton of Valais.

In this study, BAK Economics provides an overview about the current state of the hyperloop / vactrain technology. The advantages and disadvantages compared to traditional transport options are discussed, and the top companies, universities and research institutes taking on this challenge are identified. Moreover, a focus is placed on the commercial prospects of the proposed research center proposed by EuroTube.

The structure of the report is as follows. In chapter 2, we give an overview that presents a definition of the term hyperloop and describes the core technologies. Chapter 3 focuses on the advantages and disadvantages of the technology compared to other transport modes. Chapter 4 introduces the key companies, universities and research organizations. In chapter 5 and 6, we present the results of a patent and media data analysis, respectively, that assesses which companies and universities are the technology leaders and most active in topics regarding vacuum transportation technology and its commercial conversion. Chapter 7 delivers the results of expert interviews on the outlook for vacuum transport and the position of Switzerland in this field. Chapter 8 concludes the report with an assessment of the prospects and risks of the EuroTube research project.

# 2 Hyperloop: definition and core technologies

The goal of this chapter is to give an overview about vacuum transportation that includes the definition of the term hyperloop and describes the core technologies.

## 2.1 The term hyperloop: a variant of vacuum transportation

The term “hyperloop” was coined by Elon Musk in 2013.[3] Musk proposed a transportation system between Los Angeles and San Francisco that would propel passengers and/or cargo through low-pressure tubes above or below ground thus reducing aerodynamic drag and enabling travel at high speeds.

However, the idea and core concepts of hyperloop – using low pressure tubes to transport goods and/or people - have been around for a long time. In 1799, inventor George Medhurst first suggested moving goods through cast-iron pipes using air pressure. In the 19th century, several pneumatic railways were built in Europe and in the US, and most major cities employed pneumatic tube systems to transport mail and other messages. Pneumatic tubes are still used today on a smaller scale, but their relevance has diminished due to technologies such as the Internet and e-mail.

In 1904, the concept of a vacuum train (for short: “vactrain”) that would move in evacuated tubes or tunnels was developed by the inventor Robert Goddard. A vactrain could hypothetically reach hypersonic speed by employing magnetically levitating trains in evacuated (airless) tubes. In 1972, a study conducted by the RAND Corporation concluded that high-speed “tubecraft” was technologically feasible.

Musk’s hyperloop proposal in 2013 revived the vactrain idea and suggested operating at low-pressure instead of in a perfect vacuum. Musk was not the first to propose this. Other concepts looked at similar types of vacuum transportation as early as the 1980s. In Switzerland, the Swissmetro vacuum train project was the subject of many discussions in the last decades. The Swissmetro underground vactrains are supposed to connect major cities in Switzerland and lower travel time. However, due to the high costs and uncertainties associated with building the vacuum tunnels, Swissmetro and other vactrain concepts have never been built up to this day.

Therefore, Musk’s hyperloop is not a new concept, but rather a specific version, or an update, of a vactrain. After Musk’s proposal, the idea of vacuum transportation regained popularity and companies and universities around the globe started their own research activities. Many companies and universities have adopted the term hyperloop for their projects. However, other terms are also used such as, for example, “hypertube” in South Korea or “ultra-high-speed vacuum maglev” in China. Both hyperloop projects and otherwise named vactrain approaches have been analyzed in this report. Due to the large overlaps between hyperloop and other vactrain approaches, the terms hyperloop and vactrains have been used interchangeably for all vacuum transportation projects in subsequent chapters.

[3] Musk (2013): https://www.spacex.com/sites/spacex/files/hyperloop_alpha.pdf

## 2.2 Core technologies

There are different approaches to hyperloop / vactrains, but almost all versions consist of some form of levitated capsules or trains that move through low-pressure tubes. Due to the levitation of the capsules and the low-pressure tubes, both friction and air resistance are minimized, which are the main obstacles to achieving high speeds. Moreover, since low air pressure reduces drag, only a relatively small amount of electricity is needed to cruise at high speed. Power is only really needed to accelerate and to brake.

In the following, the core technologies are discussed:

- **Levitation:**
  There are several proposed methods for handling vehicle levitation and propulsion. The original Hyperloop Alpha proposal by Elon Musk suggested using air-bearings for levitation. However, most companies use magnetic levitation (or maglev, for short) instead of air-bearings to induce levitation at even higher efficiencies.[4] Magnetic levitation is based either on electrodynamic suspension (repulsive magnetic forces) or electromagnetic suspension (attractive magnetic forces)). Active maglev is already an established technology that is used by high-speed maglev trains such as the TransRapid that float over the tracks instead of rolling along them. However, these active maglev systems have their downsides as they require constant power for the electromagnets on the track and they are also expensive and complex.[5] In addition, compared to hyperloop, maglev trains face added air resistance which limits their top speed. There are only a few maglev train connections currently in use. The Shanghai airport maglev is the world's fastest maglev train with a top speed of 431 km per hour. However, both China and Japan are planning new high-speed maglev lines.

  To save costs, several companies are developing passive maglev technology where permanent magnets are placed on the underside of the capsules. When these magnets move over the conductive arrays in the track, they create a magnetic field that pushes the pod up. This aims to result in a lighter, more affordable track system while avoiding active levitation components which would span the entire tube length. Therefore, passive maglev is thought to be cheaper than traditional active maglev systems.

- **Propulsion:**
  Several methods have been proposed for propulsion. In most cases thrust from linear motors propels the pods forward and induces the levitation effect. Linear Induction Motors (LIM) or Linear Synchronous Motors (LSM) are used by most companies. A LIM performs best in terms of costs and reliability, however with its current technology, a LIM is not able to reach the same speed as an LSM.[6] In general, linear motors are proven technologies that are already widely used in a variety of wheeled-rail and maglev systems, including several rapid transit and/or people-mover systems, however, future research and tests are needed

[4] Decker et al. (2017): https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001624.pdf
[5] https://www.wired.com/story/guide-hyperloop/
[6] Delft Hyperloop (2019): https://hyperloopconnected.org/2019/06/report-the-future-of-hyperloop/

to ensure safety and reliability at the targeted high speeds of 1000 km per hour.

- **Tube materials:**
  Hyperloop tracks will be built either above ground on concrete columns, underground, or underwater within tunnels in order to maintain a relatively straight trajectory. The selection of the most suitable materials for the tubes is an important challenge. A major technical challenge associated with the tube design is how to ensure that the entire length is kept airtight.[7] Any ruptures or openings in the tube might result in pressure differences. Moreover, hyperloop must be sufficiently lightweight to ensure that fixed capital costs of construction, when compared to conventional elevated HSR or maglev systems, would be decreased. Steel, concrete and composites are typically mentioned as potential construction materials. Elon Musk suggested using steel tubes that are supported by pylons. Concrete is a versatile material and has the advantage of being easier and cheaper to manufacture than steel. By contrast, EuroTube plans to use a textile-reinforced concrete for the shell of the vacuum tube.[8]

- **Capsule:**
  The capsule design has to take aerodynamically optimized shapes into account to minimize aerodynamic drag. The selection of materials is also an important element of the capsule design as the capsules must be light-weight and safe. The stress of loads, extreme speeds, and internal air pressure all have to be taken into account in vehicle design and materials selection. Most companies currently deploy carbon fiber for their capsules.

- **Vacuum:**
  The optimal tube pressure depends on the pod frequency in the tube: the more pods in the tubes, the more efficiency is gained when the pressure is lower because all pods will then experience reduced aerodynamic drag and, thereby, reduced power consumption. However, very low pressure is more difficult and costly to maintain. Vacuum pumps, valves and airlock chambers between the tubes and the atmospheric pressure in stations are necessary to maintain a low-pressure environment in the tubes.

- **Communication systems:**
  Hyperloop pods are designed to move autonomously through the tubes. Therefore, constant connection to infrastructure, the internet and the control center is required. A reliable communication system enables stable guidance of the pod and thus improves the safety of all passengers. However, hyperloop faces additional new challenges mainly due to its unique characteristics such as its steel tube, low pressure, and high speeds. The design of the hyperloop communication system needs to overcome these challenges to provide a reliable and high-speed connection between the hyperloop pod and infrastructure.[9] Current communication technologies that are employed in high-speed railways are not suited for the high speeds of hyperloop. The main challenge lies within the communication from the pod to the outside world, which is necessary to exchange data. Optical wireless communication is a technology that has the

[7] Santangelo (2018): https://transsyst.ru/transsyst/article/view/10839
[8] https://eurotube.org/alphashell-unveil-at-epfl/
[9] https://hyperloopconnected.org/2020/02/communications-in-a-near-vacuum-environment/

potential to solve this challenge. Moreover, it is expected that new communication protocols such as 5G will allow for significant improvements in communication systems in the future.

- **Superconductivity**
  Conventional electronic systems are based on components such as cables and wires that have a certain electrical resistance. However, there are also materials in which this is not the case – at least at very low temperatures. These are called "superconductors" and their electrical resistance drops abruptly to zero when the temperature falls below a critical level. This reduces power consumption considerably. To produce materials that remain conductive even at room temperature would be a scientific breakthrough.

  Hyperloop systems could benefit from superconducting materials. For example, the Japanese SCMaglev system that is supposed to connect Tokyo and Nagoya by 2027 uses an electrodynamic suspension (EDS) system which has superconducting magnets installed. China's Southwest Jiaotong University is also researching the use of high-temperature superconducting maglev. EuroTube also plans to research linear motors that use superconducting magnets and therefore require less power at its planned test center in Switzerland. However, the costs of superconducting magnets are still very high, which makes them unfeasible for most planned commercial hyperloop tracks.[10] It remains to be seen if research progress can bring these costs down enough.

## 2.3 Conclusion

Many core technologies for vacuum transport such as magnetic levitation are well developed and have been tried and tested in applications such as the Transrapid. However, the combination of maglev technology with vacuum tubes over long distances still requires extensive testing before the best technological combinations will be discovered, the remaining technological challenges can be overcome, and commercial tracks can become feasible. The numerous test tracks planned will play a crucial part in further advancing the technological readiness of hyperloop vactrains. It is very difficult to forecast a precise date, but in our view, it seems realistic that hyperloop could achieve technological readiness within the next 10 years.

[10] https://innovationorigins.com/hyperloop-would-also-benefit-from-superconductivity/

# 3 Advantages and disadvantages of vacuum transport

This part of the chapter contains a brief overview of the advantages and disadvantages of vacuum transportation compared to existing transport options.

### 3.1.1 Travel speed and time

The key appeal of hyperloop is to provide a new form of high-speed travel. As the low-pressure tubes reduce air resistance, hyperloop capsules can travel much faster than traditional transport options such as trains and cars. According to Musk's white paper hyperloop can reach a top speed of more than 1200 km per hour. Taking into account gradual acceleration and deceleration speeds, this would average 965 km per hour for the proposed route from LA to San Francisco. It must be noted, though, that no hyper-loop test has reached a speed even close to this yet. Most of the public speed records have been set on SpaceX's 0.8-mile test track in Hawthorne, California. Munich-based TUM Hyperloop currently holds the public speed record with 288 mph reached at the latest hyper-loop pod competition in 2019. A simple explanation for why nobody has achieved the promised top speeds is that there is no track yet that is long enough. According to Delft Hyperloop (2019), a hyperloop track would need to be at least 44 miles long to allow for top speeds.

If hyperloop indeed reaches a top speed of 1,200 km per hour in the future, it would be 2 to 3 times faster than high-speed rail and 10 to 15 times faster than traditional rail. It would also be faster than maglev trains. The limiting factor for maglev trains is air resistance. Therefore, the practical limit for maglev vehicles is around 500 to 600 km per hour since air resistance is proportional to the cube of the vehicle's speed.[11] Trying to go faster would become really energy intensive. Hyperloop would also be faster than commercial jet aircraft that cruise at about 925 km per hour. Therefore, Hyperloop would indeed be the fastest transport mode regarding station-to-station travel time.

**Tab. 3-1 A comparison of station to station travel**

| Route | Distance | Hyperloop | Train | Plane | Car |
|---|---|---|---|---|---|
| Basel - Paris | 413 km | Around 30 minutes | 3 hours | 1 hour 15 min | around 5 hours |

Based on data from Google Maps and estimations according to the average speed of hyperloop

However, station-to-station travel time is only one of several components to consider in a comparison of travel time. Other factors include things such as access/egress time, the time needed for security screening, boarding, and baggage handling. These additional components currently impact travel times most significantly for flights.

- **Access/egress time:** Access/egress time is an important factor as it depends on where terminals are located. Since hyperloop capsules cannot use existing rail routes and stations, new routes must be built. It is likely that these new hyperloop stations will be built outside of cities because the construction of

[11] Cassat, Bourquin (2011) – MAGLEV- Worldwide status and technical review

new hyperloop infrastructure inside of cities is difficult and costly. A reasonable option could be to build them close to existing airports to utilize existing infrastructure and enable easier access for cars. However, access/egress time would then be significantly higher than with trains since most airports are located outside of cities. This would undermine the overall speed advantage of hyperloop compared to trains and cars.

- **Security screening**: It is difficult to estimate how much time will be needed for security screening for hyperloop travel. For example, it is unclear at this point if strict security screening like the one at airports would be necessary. Elon Musk and Hyperloop One suggest that screening would be required, whereas Hyperloop Transport Technologies claims that hyperloop will be easy to use like trains. Considering that hyperloop routes would be high profile assets, they might be vulnerable to terrorist activity which would indicate that security screening is likely. Nonetheless, since the frequency of departure is much higher than with flights, the impact of screening on travel time would be less significant because no additional buffer time would be necessary to account for delays at security.

- **Boarding process**: Boarding should be relatively fast for hyperloop due to the expected high frequency of departure of hyperloop pods which would reduce waiting time. This would be an advantage com-pared to planes. However, operating under extremely low pressure makes it necessary to design complex entry and exit systems, including airlocks for the transition from atmospheric pressure to a near-vacuum and vice versa. This could increase boarding time.

- **Baggage handling**: Baggage handling would likely be similar to planes because luggage probably needs to be stowed in a separate portion of the hyperloop capsules and would require special handling. This would be a disadvantage compared to (maglev) trains where people can handle and store their own luggage themselves and avoid additional baggage handling time.

All in all, it seems highly likely that the time advantage of hyperloop will decrease somewhat due to the aforementioned factors that increase overall journey times. Nevertheless, hyperloop would still have a significant time advantage compared to other transport modes for many connections. This would have a significant impact on work, travel and leisure options as well as real estate markets. Hyperloop would, for example, allow for much longer commutes, i.e. it would be possible to live in Basel and commute daily to Paris or vice versa. One could also visit the opera or a restaurant hundreds of kilometers away and be back home the same evening.

The high speed of hyperloop could also make it into an option for high-speed cargo transport. The portion of the freight market that might be interested in the high speeds offered by hyperloop would likely be the current market for air freight which accounts for just 2 percent of ton miles, but presents 40 percent of freight value.[12] The rise of e-commerce, same-day deliveries and the evolution towards on-demand logistics will lead to a fast-growing global freight transport in the coming years and decades. Air freight is set to double over the next 20 years.[13] This will strain the air traffic

[12] Taylor et al. (2016)
[13] https://hyperloop-one.com/blog/new-cargo-brand-built-demand-world

infrastructure and lead to a further increase of greenhouse gas emissions. Hyperloop could be an alternative for high-priority, on-demand goods such as fresh food, medical supplies, electronics, and more.

### 3.1.2 Costs

The costs of transport modes can be separated into capital costs, operating costs, and overhead costs. The capital costs are the costs of building the infrastructure (tracks, stations) and the costs of purchasing the vehicles. The operating costs are the cost of maintenance of the infrastructure and vehicles as well as the costs related to the operation of the vehicles and stations. The overhead costs comprise the capital and maintenance cost of real estate and the staff costs in addition.

Hyperloop companies promise that new hyperloop routes can be built at a lower cost than rail connections. According to Elon Musk's white paper, the proposed hyperloop route from Los Angeles to San Francisco will cost only $7.5 billion. This should allow for affordable ticket prices at an estimated 40 US Dollars per roundtrip. By contrast, high-speed rail connection between the two cities has an estimated cost of $68.4 billion. However, a large part of the costs of the high-speed rail project can be attributed to connecting the rail lines to cities' downtown areas where land is particularly expensive. This is a key difference to the hyperloop project which would connect the outskirts of the two cities.

Musk argues that the cost advantage should come from lower land acquisition costs, as the hyperloop is supposed to be built on pylons on top of existing highways. Moreover, he projects that energy costs should be very low since all energy is supposed to be created by solar cells on the tube. However, these projected cost numbers from Musk's white paper seem unrealistically low. Musk calculates $16 million per mile, whereas other hyperloop companies, such as Virgin Hyperloop One, give an estimated average cost of $25-27 million per mile just for the needed technology excluding land acquisition. The cost of construction for the planned Abu Dhabi route is currently even higher at an estimated $52 million per mile excluding land acquisition. An underwater track from Helsinki to Stockholm is estimated to cost $64 million per mile.[14] Underwater tunnels will be more expensive than tunnels under land, because the emergency evacuation and fire accessibility requirements are more difficult to implement.

This large difference in cost estimates shows that cost calculations for an as-yet inexistent system such as hyperloop are inevitably highly uncertain. As there is no completed route yet, there are no reliable benchmarks available. For example, it is difficult to project how costly it will be to maintain a partial vacuum in long-distance routes, as it has not been tested yet. It is also difficult to project operating costs such as infrastructure maintenance, system control costs, etc. Moreover, the proposed construction on pylons could cause additional costs instead of resulting in cost savings aspired for with such elevated construction. Another key question is whether hyperloop connects city centers or city outskirts; the latter option would be significantly cheaper due to lower land acquisition costs and fewer requirements for tunneling at the expense of longer travel duration.

[14] Walker (2018)

The capital cost for building a hyperloop will also heavily depend on the local conditions. Building in a relatively empty area on flat sandy soil such as in the Middle East will be cheaper than building in a city or in the mountains. In the case of Switzerland, the landscape would require expensive, large-scale tunneling, which would boost costs significantly. For example, a connection between Bern and Zurich would require tunnels for approximately 62 percent of the route.[15] However, tunnel costs of hyperloop will likely be lower than for rail because a smaller diameter of tunnel is required.[16] Tunneling could also speed up the planning process and reduce issues associated with acquiring rights of way. Nevertheless, tunneling costs need to decrease so that hyperloop tracks become commercially feasible. The Boring Company promises to reduce tunneling costs in the future by a considerable amount; however, it remains to be seen if their ambitious targets can be achieved.[17]

Hyperloop will offer less flexibility concerning the design of the route because, in order to maintain comfort for most people, sharp curves won't be possible. According to Doppelbauer (2018), a lateral acceleration of 0.1 g should not be exceeded, if the comfort level should equal that of a regular high-speed train. This implies that the curve radius at an operating top speed of 1200 km/h would exceed 100 km. Steeper curves would require significantly lower speeds. When 0.5 g lateral acceleration are considered as acceptable, the curves still need a minimum radius or 23.5 km. Therefore, while hyperloop could possibly be built on top of some highways in the US, this approach does not seem feasible in Europe as highways have too many curves. This will affect land acquisition costs.

In summary, it seems questionable that hyperloop construction will be significantly cheaper than regular train routes or even maglev trains. Previous active maglev train projects have proven expensive which, so far, has prevented more widespread commercial success. While hyperloop companies plan to save money by using passive maglev solutions and by foregoing concrete guideways, there will also be new costs of additional features such as tubes, airlocks and vacuum pumps. Therefore, the construction costs of hyperloop and regular maglev trains might be comparable in the end.

Considering the combination of high cost and relatively low passenger capacity, low ticket prices will have difficulty covering the costs of hyperloop connections. But high prices would decrease the demand for hyperloop connections. So far, funding for research and test routes of hyperloop companies has come mainly from private companies such as Virgin. However, in order to build commercial routes, public subsidies will most likely be necessary. High costs will not necessarily stop the construction of routes if there is a political will to invest in this new technology. For example, new high-speed rail lines are planned or under construction even though many existing lines in developed countries also cannot refinance themselves and depend on subsidies due to lack of demand or higher than expected construction costs.

However, given the high fixed costs related to the construction of hyperloop tracks, it seems unlikely that hyperloop will be able to compete with air travel for long-distance travel.

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[15] https://ssc.ethz.ch/2017/03/ein-unterirdisches-flugzeug-ohne-fluegel/
[16] Van Goeverden et al (2018)
[17] https://www.boringcompany.com/faq

### 3.1.3 Capacity

An important factor concerning the commercialization of transport modes is capacity. Capacity is defined by the maximum number of vehicles and passengers which can pass through a reference location in a given period of time.

The size of a hyperloop pod is quoted by several companies to be in the range of 25 to 40 passengers in order to keep the dimensions of the tube reasonably small.[18] However, some companies plan to build larger pods that are closer to metro wagons. For example, the Swissmetro concept is based on relatively large wagons.

Elon Musk claims in his white paper that pods can depart as frequently as every 30 seconds during peak periods. This would result in a capacity of 3,360 passengers per hour. Similarly, Hyperloop TT suggests a capacity of 3,600 an hour based on pods holding 40 people departing every 40 seconds.

However, due to safety concerns it is unlikely that such high frequency can be achieved. Walker (2018) calculates that hyperloop pods traveling at up to 760 miles per hour will have a maximum deceleration of 0.5 g. At that rate of braking, it will take pods 68.4 seconds to come to a full stop, for example, in case of an accident somewhere along the tube. Safe vehicle operation dictates the minimum headway between vehicles should be equal to the distance required for the vehicle to stop safely. Therefore, Walker concludes that the minimum separation of pods is around 80 seconds which would allow only 45 departures per hour. This would reduce the maximum hourly capacity to 1,260 (28 people per pod) or 1,800 (40 people per pod). Doppelbauer (2018) argues that the maximum deceleration is only 0.3 g (double the braking performance of the Transrapid maglev train), therefore, he concludes that a frequency of 2 minutes is realistic, i.e. 30 departures per hour. Van Goeverden et al. (2018) calculate an even lower frequency of only 12 departures per hour.

These different estimates illustrate that forecasts for passenger capacity of hyperloop connections are highly uncertain. Capacity could be increased using multiple tubes, but this would cause significantly higher costs. Another way to increase capacity would be the use of larger pods such as in the Swissmetro design, but this would likely also include higher costs for the tubes and/or the propulsion and levitation systems.

Regarding cargo transport capacity, the main obstacle is limited handling capacity in the pods that are currently planned by most hyperloop companies. Adding the capability for full container shipping would require a tube of a much larger internal diameter. But by trans-loading freight from full sized containers into smaller “air cargo” type containers, hyperloop could still capture some of the current air freight market, even with a smaller diameter tube.

Moreover, hyperloop might be an option to facilitate offshore extensions to current port facilities, many of which are capacity constrained. Unloading containers from ships on offshore platforms which transfer containers through a hyperloop tube to be brought inland for sorting and distribution could provide much-needed expansion of port

[18] Doppelbauer (2018)

facilities. Hyperloop TT has been developing technology solutions for container shipping as part of its joint venture with HHLA, the operator of the Hamburg port.

### 3.1.4 Energy consumption/ Greenhouse gas emissions

According to hyperloop advocates, a key advantage of hyperloop is that it needs less power to travel than most other transport means and, therefore, generates less greenhouse gas emissions. Findings from Taylor et al. (2016) conclude that hyperloop should be about two to three times more energy-efficient than high-speed rail and much more energy-efficient than air travel on a passenger mile basis. Estimations from the EPFL also conclude that hyperloop would be more energy-efficient than regular trains.[19] Hyperloop achieves this higher energy efficiency due to the elimination of air resistance and friction in the tubes. The downside is that the tubes need constant energy to maintain the vacuum inside, but the former effects should outweigh the latter in terms of energy consumption.

By contrast, one advantage of regular trains is that a lot of train infrastructure is already there, meaning there is less energy needed for the construction of new tracks as new trains can use old infrastructure as well. However, new high-speed trains also often cause conversion costs.

In the hyperloop alpha white paper, the hyper connection from L.A. to San Francisco is powered by solar cells on top of the tubes and by batteries when the sun isn't shining. Most other hyperloop companies also stress the importance of renewable energy as a power source for their planned hyperloop connections. Hyperloop could therefore be a more environmental-friendly transport alternative. However, differences in the "grid" play a role which refers to the average local power mix. In Switzerland, 80% of electricity comes from renewables or nuclear power, therefore, the advantage for hyperloop compared to trains powered by the grid would be lower. Moreover, conventional or maglev trains could also be powered completely by renewable energy.

While power from solar cells on top of the tubes seems feasible in California, there might not be enough solar power available for routes in northern regions such as Helsinki to Stockholm, especially in winter. Walker (2018) argues that regardless of location, powering hyperloop directly through renewables would be largely inefficient and it would be more cost-effective to generate renewable energy through large-scale solar arrays (or through wind or hydro power) which could be used to power hyperloop via the grid.

In summary, hyperloop has a clear advantage compared to air traffic when it comes to energy efficiency and greenhouse gas emissions. Hyperloop is also more energy efficient than trains, but the advantage in terms of greenhouse gas emissions depends on conditions such as the average local power mix.

### 3.1.5 Safety

In general, hyperloop transport has the prerequisites to becoming a very safe means of transport. It is designed as a completely automated system that will minimize accidents or delays due to human error. Because the tube design of hyperloop is a closed

[19] https://www.nzz.ch/wissenschaft/lausanne-bekommt-eine-eigene-hyperloop-teststrecke-ld.1516784

system, it will make it resilient to weather conditions and, in addition, will avoid accidents with other transport means or wildlife because there will be no at-grade crossings.

However, there are several safety issues that would need to be solved by extensive testing at high speeds before commercialization could succeed. These issues include depressurization due to pressure leaks, evacuation of people in case of accidents or terror attacks, stranded capsules, incorporation of emergency exits, etc.

Moreover, extremely high speeds of 1,200 km/h require advanced communication subsystems. For example, the detection of the exact location of all pods needs to be extremely reliable. Another issue is the problem of safe braking of the vehicles, together with the corresponding safe dissipation of the corresponding braking energy.

To increase passenger safety, hazard mitigation methods need to be incorporated within the design phase. For example, a redundant power supply system and back-up communications systems are necessary. Moreover, life support systems on the pods are needed in case of pressure loss and it will be important to have the ability to repressurize the tube quickly.

### 3.1.6 Distances

According to Musk's Hyperloop Alpha paper, hyperloop connections make the most economic sense for medium distances (up to 900 miles). For example, it would allow much longer commuting distances, i.e., people could work in Basel and live in Paris. A downside is that hyperloop is optimal for direct travel between two places and it is economically less feasible for allowing stops along the way at multiple destinations as several accelerations and decelerations would increase energy consumption significantly.

Another possible use for hyperloop is for short-distance travel for fast connections between, for example, two airports. However, at these short distances, the speed advantage partly disappears due to factors such as access/egress time, security screening, baggage handling, etc. (see chapter 3.1.1). Therefore, it seems difficult for hyperloop to compete with traditional trains on short-distance connections such as between the cities Basel, Zurich and Bern. An example of this is the maglev train at the airport pf Shanghai, China. While it travels at a much higher speed (up to 430 kilometers per hour) than regular trains, the maglev only connects Pudong Airport with Longyang Lu subway station on the outskirts of the city (a ride of 30 km). As a result, demand for maglev train tickets is low because the time gained at high speed mostly disappears because travelers must take additional transport options to reach the city center.

Still, short connections such as between an airport and a city center could be prestigious pilot projects that show that it is possible to create hyperloop tracks and advance the development of this futuristic technology.

For longer distances, the fixed infrastructure costs of most hyperloop companies are expected to become too high compared to air travel. However, there are exceptions, for example, Chinese CASIC and ET3 Global Alliance both plan to build long-distance connections in the future.

### 3.1.7 Further aspects

There are several further advantages and disadvantages of hyperloop compared to traditional transport means:

**Advantages:**

- Hyperloop will create less noise than airplanes, trains, and cars because pods are not in contact with the tube, low air pressure and the tube is a closed system.
- As there is no friction between pod and tube, there will be hardly any material abrasion. This should lower maintenance costs compared to other transport means.

**Disadvantages:**

- Most hyperloop designs call for relatively small pods in which people probably won't be able to move around while traveling due to the pod's high acceleration and speed. Therefore, it is likely that the customer's level of comfort in hyperloop will be lower when compared to traditional transport means. However, some design plans are closer to metro wagons where people can move around. This shows that it is still uncertain how the final design of hyperloop / vactrain pods will look like in the end.
- The magnets and batteries needed for the capsules and tubes will require a large amount of rare earth materials. This could lead to a dependence on China, as most rare earths are mined in China.[20]
- Hyperloop is a completely new system. Therefore, it cannot rely on existing railroads or streets whereas other new transport innovations such as high speed rail or electric cars, for the most part, can.

There are also still several challenges that need to be solved before the commercialization of hyperloop can succeed. These challenges include:

**Regulations, standardizations and certifications:**

- New regulations, standardizations and certifications for the hyperloop system and operation parameters including, but not limited to, tube size, operating pressure, operating speed, and guideway layout, are all needed. Testing the vacuum system and the structural behavior of a full-scale tube will be crucial before standardization can take place. Some legislation can be derived from (maglev) trains and aircraft, as these share some similarities with hyperloop. In 2018, the Spanish hyperloop start-up Zeleros signed an agreement with other European hyperloop companies (Hyper Poland and Hardt) as well as TransPod from Canada to collaborate with the European Union and other international institutions on the implementation of a definition of the standards which could ensure the inter-operability and the security of a hyperloop system. In February 2020, the launch of a new Joint Technical Committee,

[20] https://www.reuters.com/article/us-china-usa-rareearth-refining/china-set-to-control-rare-earth-supply-for-years-due-to-processing-dominance-idUSKCN1TO04J

CEN/CLC/JTC 20, dedicated to hyperloop systems standardization, was announced in Europe.[21]

**Thermal stress**

- Thermal load effects are another difficult challenge because changes in temperature induce thermal stress on the tube structures. For example, in sunny areas, the top surface of the tube will heat up and, hence, expand more than the underside of the tube. This could cause unwanted contact between the pod and the tube. Thermal expansion has been a problem with large tubular structures for a long time. Oil pipelines also use a variety of technologies such as expansion loops to overcome this obstacle. Elon Musk (2013) suggested slip-joints as an answer to this problem, however, many of the technicalities have yet to be addressed. The choice of materials also matters in this regard.

**New competitors**

- Another challenge is any other new means of transport that could ultimately decrease the appeal of hyperloop. In particular, there is an extensive amount of research into making air travel faster and/or more efficient. For example, supersonic flights would allow for even higher speeds than hyperloop. Startups such as Boom Technology, as well as large companies such as Boeing and Lockheed Martin, are working on the development of such supersonic flights. These companies, however, still face many challenges such as unacceptable noise and high costs. SpaceX and Virgin Galactic even plan to offer sub-orbital flights in the future which would increase travel speed even further. However, it is uncertain if commercial sub-orbital flights will ever be realized. A more realistic option in the mid-term is the increasing use of fuels produced from renewable electricity, $CO_2$ and water via power-to-liquid processes as an alternative fuel source for aviation that reduces emissions and, therefore, reduces one of the main downsides of current commercial air travel.[22]

## 3.2 Conclusion

The conclusion of chapter 2 was that many core technologies for vacuum transport are well-developed and that hyperloop could achieve technological readiness within the next 10 years. However, while technological readiness is a necessary factor of success, it is not sufficient for commercial implementation. Hyperloop also needs to offer clear advantages to existing transport means.

The review of the research literature on vacuum transport shows that hyperloop has certain advantages such as higher speeds and better energy efficiency. The speed advantage appears to be particularly attractive for medium distances (between 300 km and around 1,400 km) because factors such as access and egress time reduce the speed advantage for shorter distances. However, the lower cost estimates compared to high-speed trains that are promised by several hyperloop companies seem unattainable. Even though advances in passive maglev will possibly reduce costs, the

[21] https://www.cencenelec.eu/news/articles/Pages/AR-2020-003.aspx
[22] https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off

construction of vacuum tubes over hundreds of kilometers will be the main cost driver. Costs will be particularly high in areas that require extensive tunneling such as in Switzerland.

Therefore, the best prospects for the construction of the first commercial vactrains appear to be in areas where there are no geographical obstacles and where there is not already an extensive infrastructure system established. Political support is an important necessity as the construction of the first commercial tracks will most likely require significant public spending and will carry risks such as budget overruns due to the novelty of the technology.

# 4 Top companies and universities

Interest in hyperloop / vactrains has risen sharply in recent years. Many corporations and universities around the globe are currently working on R&D and feasibility tests. In this chapter, the most important hyperloop companies and universities are presented.

## 4.1 List of hyperloop / vactrain companies (in alphabetical order):

**China Aerospace Science & Industry Corporation**

The China Aerospace Science & Industry Corporation (CASIC) is a large state-owned hi-tech company that plans to combine supersonic flight technology with rail transit technology. CASIC is researching the use of superconducting maglev technology in vacuum tubes. First, it plans to build a regional network in China with vactrains that reach speeds between 370 and 620 miles per hour. Later, an intercontinental hyperloop train with a top speed of over 2,300 miles per hour is planned that could become part of China's Belt and Road.[23] In contrast to most hyperloop concepts that are based on compact pods, CASIC aims to move long capsules of up to 36 meters through the tubes.

**China Railway Construction**

China Railway Construction Corp (CRCC) is a state-owned construction enterprise based in Beijing, China, that, in terms of revenue, is one of the largest construction and engineering companies in the world. Two subsidiaries of this company -- China Railway Maglev Transportation Investment and Construction Co. and China Railway Fifth Survey and Design Institute Group -- plan to cooperate with Hyperloop TT to build a 10-kilometer hyperloop test track in China and, later, a longer commercial track if the test track proves successful.[24]

**DGWHyperloop**

Established in 2015, DGWHyperloop is a subsidiary of Dinclix GroundWorks, an engineering company based in Indore, India. DGWHyperloop's initial proposals include a hyperloop-based corridor between Delhi and Mumbai called the Delhi Mumbai Hyperloop Corridor.

**Elon Musk / SpaceX / The Boring Company**

Elon Musk revived global interest in vacuum transportation with his Alpha Hyperloop paper in 2013. SpaceX is a private American aerospace manufacturer and space transportation services company led by Elon Musk. It doesn't develop hyperloop solutions itself, but it organizes and sponsors the annual Hyperloop Pod Competition and provides the infrastructure for the competitors at its hyperloop test route in California. The Boring Company is another company led by Elon Musk that focuses on infrastructure and tunnel technology that can be used to construct hyperloop routes. The Boring Company promises to decrease tunnel costs tenfold in the future, which would be very important for the feasibility of hyperloop tracks that include tunnels.

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[23] https://www.forbes.com/sites/wadeshepard/2017/09/13/how-chinas-belt-and-road-just-sparked-a-renaissance-of-technological-innovation/#7d743ce738f7

[24] https://www.scmp.com/news/china/article/2156091/remote-chinese-city-hopes-board-hyperloop-express-after-signing-deal-us

**ET3 Global Alliance**
ET3 Global Alliance is an American consortium of licensees dedicated to the global implementation of evacuated tube transport technologies. ET3 was founded in 1997 with the goal of establishing a global transportation system utilizing car-sized capsules via frictionless superconductive maglev in an almost complete vacuum. Most ET3 licensees held outside of the USA are held in China. Licensees can incorporate the IP of ET3 at the cost of royalty on revenue from future hyperloop tracks. However, there is no prototype or test track from ET3 to this day.

**Hardt Global Mobility**
Hardt Global Mobility was founded in 2016 in Delft and emerged from the TU Delft Hyperloop. Large corporations such as Deutsche Bahn, Continental, Tata Steel and Swiss ABB have invested in Hardt. The Dutch team has set up a full-scale testing center for hyperloop technology in Delft and plans to build a 3-kilometer test track in the Netherlands. Hardt hopes to launch the first commercial connection by 2025. Hardt has developed a switch technology that allows the pods to pass from one track to another. This could be used to create a network of tubes connecting all European cities.

**Hyper Chariot**
Hyper Chariot is a startup company based in Santa Monica, United States. On July 27, 2017, it announced a partnership with AML Superconductivity and Magnetics for the development of a vehicle and a propulsion system.

**Hyper Poland**
Hyper Poland is a Polish hyperloop startup that was founded in 2017.

**Hyperloop Transportation Technologies**
Hyperloop Transportation Technologies (HTT) evolved from a crowdfunding campaign in 2013. In 2020, HTT plans to open a test track at its research facilities in Toulouse, France. HTT's pod, Quintero One, is constructed out of a dual-layer composite material created using carbon fiber and embedded sensors. HTT is beginning the process of integrating its full-scale passenger capsule for human trials in 2020. HTT has an exclusive license with Lawrence Livermore National Laboratories for the use of its passive magnetic levitation technology. [25] This system does not require power to generate levitation forces.

The company plans to construct a commercial hyperloop track that would connect Abu Dhabi and Dubai.[26] It also plans to construct tracks in India, the Ukraine and China. The company teamed up with Russia's Caspian Venture Capital on a feasibility study to gauge the potential of building a 65-kilometer hyperloop between the Russian port of Zarubino and the Hunchun logistics zone in China. This could become a part of China's Belt and Road project in the future.

**TransPod**
TransPod Inc. is a Canadian hyperloop company that was founded in 2015. TransPod has partnered with companies MERMEC, SITAEL, and Blackshape Aircraft to collaborate with the development and testing of the TransPod tube system. It has since

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[25] Great Lakes Hyperloop Feasibility Study (2019): https://assets.documentcloud.org/documents/6580268/Great-Lakes-Hyperloop-Feasibility-Study.pdf
[26] http://www.globalconstructionreview.com/companies/first-phase-abu-dhabi-dubai-hyperloop-be-finished-/

expanded from its Toronto, Canada, headquarters to open offices in Toulouse, France, and Bari, Italy.

TransPod is preparing to build a test track in Canada. TransPod has also announced plans for a test track of more than 3 kilometers to be constructed in the town of Droux near Limoges. In the future, TransPod plans to develop commercial routes both worldwide and in Canada serving such routes as Toronto-Montreal, Toronto-Windsor, and Calgary-Edmonton.

**Virgin Hyperloop One**
Virgin Hyperloop One (formerly Hyperloop One, and before that, Hyperloop Technologies) was founded in 2014 and employs a team of around 300 employees. By 2017, it had completed a 500-meter Development Loop (DevLoop) in North Las Vegas, Nevada. In 2017, Hyperloop One performed its first full-scale hyperloop test becoming the first company in the world to test a full-scale hyperloop. The system-wide test integrated hyperloop components including vacuum, propulsion, levitation, sled, control systems, tube, and structures. The company uses a pod prototype, the XP-1, constructed of a structural aluminum chassis surrounded by a carbon fiber shell.

Virgin Hyperloop One has released a preliminary feasibility study for a hyperloop connection between Helsinki and Stockholm, reducing the travel time between the cities to half an hour. Other feasibility studies are underway in Russia, the United States, and the Netherlands. Moreover, the company has plans to build hyperloop connections in Dubai, Saudi Arabia, India, Canada, Mexico and the UK.[27]

**Zeleros**
Zeleros was founded in Spain in 2016. Currently, the corporation consists of a team of 20 engineers and doctors specialized in different fields, developing and testing the systems and subsystems of the hyperloop integrators. In September 2018, the corporation announced the planned construction of a 2-kilometer test track to perform dynamic tests of the system in Sagunto, Spain.

## 4.2 List of universities and research organizations (in alphabetical order)

**EuroTube and Swiss Universities**
The EuroTube Foundation was founded in 2019 to provide simpler access to public test sites and shared research infrastructures in Europe. The EuroTube Foundation's mission is to provide neutral testing grounds for research and technology at central locations in Europe. At its Swiss base in Collombey-Muraz, the EuroTube Foundation develops the necessary infrastructure technologies to facilitate its first 3-kilometer long test track that is designed to meet the needs of university research groups and the growing industrial and startup ecosystem for vacuum transportation.

EuroTube cooperates with Swiss universities ETH Zürich and EPFL Lausanne, SBB and other partners. ETH Zürich and EPF Lausanne have both participated in the hyperloop pod competitions in recent years. Swissloop – a team of students from ETH and other

[27] http://hyperloop-one.com/global-challenge-winners/

Swiss universities - built a pod run by a linear induction motor that won an innovation award from SpaceX and reached second place in the competition of 2019. The pod's chassis is comprised of carbon fiber, giving it a total weight of only 200 kilograms.[28]

Swiss EPFLoop's prototype featured a U-shaped carbon fiber skeleton with the motor on the inside and battery packs on the outside. A small pressurized chamber on top of the pod protects the electronic components and the entire pod is covered in a carbon fiber skin. The EPFL team reached third place in the 2019 hyperloop pod competition.[29] EPFL plans to build a small circular hyperloop test track in the coming years.

**Korean Rail Research Institute (KRRI)**
The KRRI was established in 1996 as a railway research body in Korea aimed at developing railway transportation and enhancing competitiveness in the industry by unfolding strategic R&D activities along with railway policies. The institute collaborates with other Korean research institutes on the development of core technologies for the near-supersonic Korean vactrain, also known as Hyper Tube Express (HTX).

**Southwest Jiaotong University**
Southwest Jiaotong University has been active in vactrain research for many years. It became the first university institution to become licensees of the ET3 consortium. The university built a 45-meter high-temperature superconducting, maglev test loop for a vacuum maglev train – the first vactrain test track in China.[30]

**TU Delft / Delft Hyperloop**
Delft Hyperloop is a student research team from the Delft University of Technology that participated in the hyperloop pod competitions. It reached second place in the competition in 2018.

**TUM Hyperloop**
TUM Hyperloop is a student research team from the Technical University of Munich that has won the hyperloop pod competition four times in a row. TUM Hyperloop currently holds the public speed record for hyperloop at 463 km per hour, which was reached at the latest hyperloop pod competition in 2019. TUM Hyperloop constructed its pod using carbon fiber prepregs from SGL Carbon.

The Bavarian state government is also supporting the mobility concept of hyperloop and plans to build a hyperloop test track in Bavaria.

**Additional universities with notable hyperloop / vactrain research activities:**

- MIT

- Madras Institute of Technology

- Stanford University

- University of Edinburgh

[28] https://ethz.ch/en/news-and-events/eth-news/news/2019/07/swissloop-in-top-3.html
[29] https://epfloop.ch/#vision
[30] https://thenextweb.com/science/2018/03/28/dont-call-it-a-hyperloop-chinese-super-maglev-said-to-be-capable-of-1000-km-h-speeds-in-the-future/

- University of Missouri

- Universitiy of Washington

- Xijing University

## 4.3 Existing test routes and planned commercial routes

To advance the hyperloop concept further as well as to overcome its various challenges, extensive testing is required. Several companies and universities are looking for opportunities to realize a test track. Currently, only a few hyperloop test routes exist. However, there are several test tracks planned for the coming years. Moreover, there are several feasibility studies underway for the implementation of commercial tracks in many countries. Most of these future commercial projects are still likely to be decades away, though.

### 4.3.1 Existing test tracks:

- SpaceX has a 0.8-mile test track at its campus in Hawthorne, California, and the company announced its intention to build a new 10-mile test track for the next hyperloop pod competition in 2020.

- Virgin Hyperloop One opened its 500-meter test track in 2017 in Las Vegas, Nevada. In 2019, HTT opened a test track at its research facilities in Toulouse, France.

- Hardt Hyperloop recently opened a 30-meter tunnel test track.

- Southwest Jiaotong University built a 45-meter high-temperature. Superconducting. maglev test loop for a vacuum maglev train in China.

### 4.3.2 Selection of planned test tracks:

- TransPod plans to build a test track in Droux (France). The track will be 3 kilometers long and operate a 2-meter diameter half-scale system and is set to open in the near future.[31] To build the track, TransPod has partnered with ArcelorMittal, Électricité de France, La SADE, and Hyperloop Limoges.

- Hyperloop TT plans to open a 320m test track in Toulouse, France, in the near future.

- Hardt Hyperloop plans to open a 3-kilometer test track in the Netherlands in 2022.[32]

- In Switzerland, EuroTube wants to open a 3-kilometer test track in the canton of Valais in 2021 (see chapter 8).

- The TU Munich has plans to open a test track on the outskirts of Munich in the coming years.[33]

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[31] https://transpod.com/en/press-room/press-releases/transpod-expands-footprint-partner-network-france-construction-test-track-system-development/
[32] https://nltimes.nl/2019/10/21/delft-hyperloop-company-build-3-km-test-track
[33] https://www.tum.de/nc/en/about-tum/news/press-releases/details/35683/

- Virgin Hyperloop One announced its intention to build the world's longest test and certification hyperloop track in Saudi Arabia.[34] The company is also planning a 15-kilometer test track in India.

### 4.3.3 Selection of potential future commercial tracks:

**North America:**
- Los Angeles to San Francisco

- Kansas City to St. Louis

- Cleveland to Chicago

- New York City to Washington, D.C.

- Chicago to Columbus to Pittsburgh

**Europe:**
- Liverpool to Glasgow

- London to Edinburgh

- Stockholm to Helsinki

**Asia:**
- Mumbai to Pune

- Riyadh to Jeddah

- Wuhan to Guangzhou

- Dubai to Abu Dhabi

## 4.4 Conclusion

On a company level, the US company Virgin Hyperloop (VHO) seems to be in the pole position because VHO already has significant test experiences at its own test track and is already in talks with many regions for potential hyperloop tracks. However, given that hyperloop development is still in the early stages of development and there are hardly any test tracks yet, there should still be opportunities for European hyperloop companies to catch up.

Among universities, the European universities TU Munich, TU Delft, EPFL Lausanne and ETH Zurich have high-level hyperloop research programs as can be seen by their excellent results in recent SpaceX hyperloop pod competitions. Asian research institutes

[34] https://hyperloop-one.com/saudi-arabia-looks-build-worlds-first-long-range-hyperloop-test-track-partnership-virgin-hyperloop-one

such as Chinese Southwest Jiaotong University and South Korean KRRI are also in a good position due to their advanced know how in vactrains and maglev technologies.

Concerning potential commercial tracks in the future, we see the highest probabilities for first hyperloop / vactrain tracks in the Middle East, India and China. In Europe and Switzerland, further technology advances to reduce tunneling costs are necessary before hyperloop can become a competitive transport option. That said, some characteristics of Europe might indeed lead it to adopt hyperloop later on if pilot projects in Asia turn out to be a success and tunneling costs decrease. First, climate targets in the EU are more ambitious than in most other regions and, therefore, the pressure to implement more energy-efficient transport options such as hyperloop is higher. Second, people in Europe are already accustomed to using public transport and, therefore, might embrace new vactrain connections faster than elsewhere.

# 5 Patent analysis

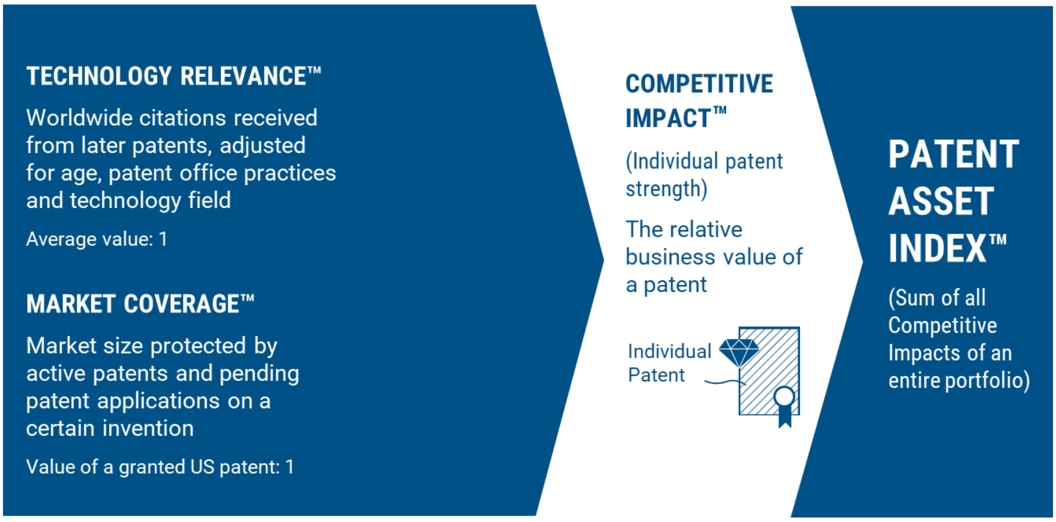
The patent analysis in this chapter gives an overview of the intellectual property of the hyperloop / vactrain research companies, universities, and research organizations. In order to compile this overview, we have cooperated with experts from the Swiss Federal Institute of Intellectual Property to create two hyperloop technology fields. First, a field that has a narrow definition of patents specifically related to vacuum transportation and a second field that includes a wide definition of patents covering hyperloop-related technologies.

To create these two technology definitions, we conducted a patent search in several international patent databases with patents and patent applications covering the technical developments of hyperloop-related technologies. For the patent search, a mixed search profile with keywords (such as maglev, hyperloop, superconduct, vac train, etc.) patent classes and company names was used.

**Valuation of patents**

In the patent analysis, the focus was not only on the number of patents, but also on the qualitative value of the patents found. For this purpose, a measurement of patent strength was carried out with the aid of two indicators: technological relevance and market coverage.

**Fig. 5-1 Valuation of patents**




Sources: Swiss Federal Institute of Intellectual Property, PatentSight, BAK Economics

Technological relevance is measured by references and citations of the patent by third parties and shows how important an invention is in comparison with other patents (competitor’s assessment).

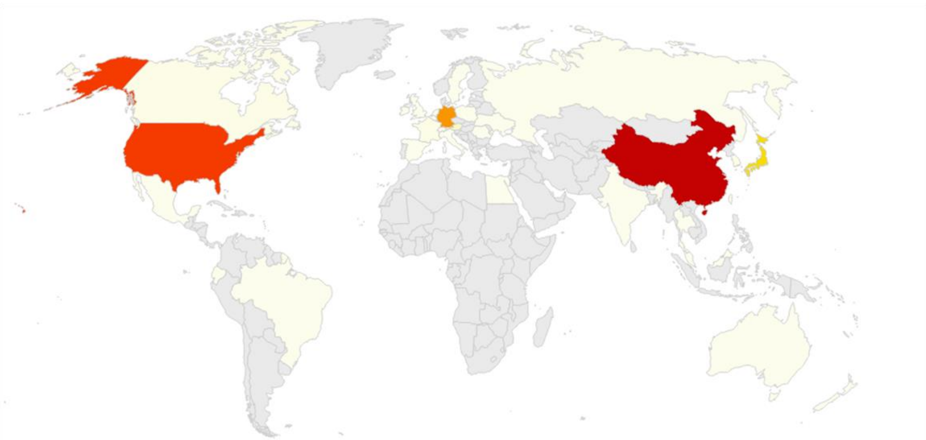
Market coverage, i.e. the statutory coverage of the patent protection, shows how companies assess the importance of their own invention. Since international patent protection is costly, launching an extensive international market coverage, therefore, signals that the patent applicant believes that its patent is promising (self-assessment).

The combination of these two indicators gives the competitive impact of each patent. The sum of all competitive impacts of an entire patent portfolio adds up to the Patent Asset Index of a specific company. As a result, the results show which countries, regions and companies are the research leaders in vacuum transportation in terms of patent data.

## 5.1 Patent analysis: broad definition

The first hyperloop technology field is based on a broad definition of the technology that includes patents for all the technologies that are linked even indirectly to vacuum transportation. This includes patents covering, for example, magnetic levitation or linear induction motors even if these patents do not specifically cover use in a hyperloop system. The idea is that these patents indicate technological know-how that might not be used for hyperloop now (i.e., a patent for magnetic levitation may be used in factories), but it could, nonetheless, be beneficial for the development of hyperloop in the near future.

**Fig. 5-2 Top R&D locations: broad definition**



| | China | USA | Germany | Japan | Austria | France | Canada | South Korea | Switzerland | Australia | United Kingdom | Netherlands | Spain | Italy | Russia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Patent Asset Index™ | 576 | 424 | 337 | 165 | 70 | 44 | 41 | 32 | 22 | 21 | 15 | 13 | 12 | 12 | 9 |
| Portfolio Size | 764 | 150 | 149 | 141 | 19 | 25 | 32 | 199 | 12 | 7 | 8 | 8 | 12 | 11 | 29 |

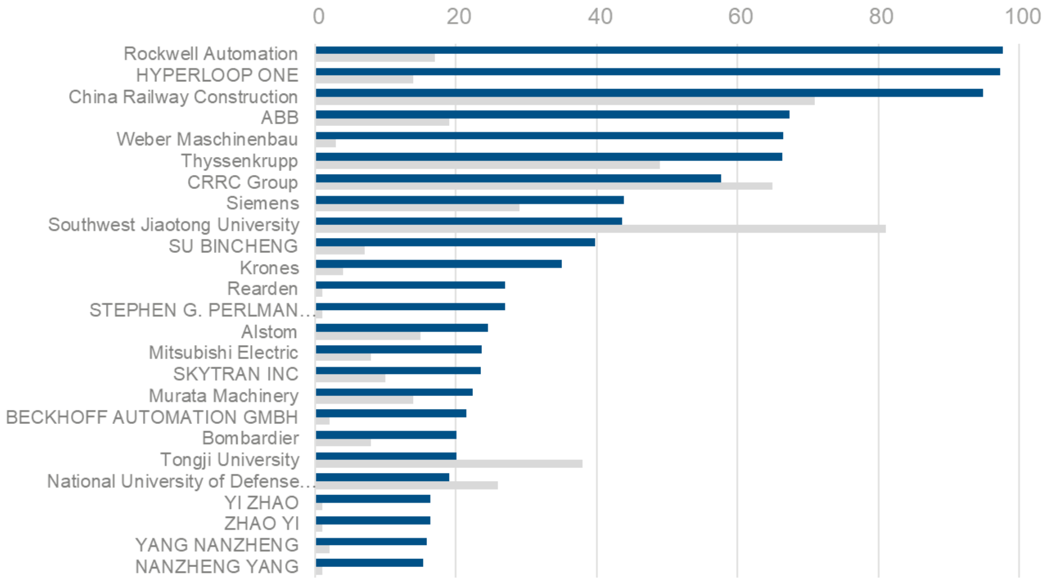
Sources: Swiss Federal Institute of Intellectual Property, BAK Economics

Using a broad definition of hyperloop, most patents have, so far, been developed in China. In 2019, there were 764 active patents in hyperloop-related technologies from researchers from China. This number is much higher than in other major countries. However, it must be noted that the nation-wide patent strategy in China explicitly aims to increase the number of its domestic patent filings, which results in key differences in patent guidelines there. Consequently, minor improvements are more likely to be granted patents in China than in other countries. Therefore, in the end, it is more useful to take the patent quality into account by looking at the Patent Asset Index.

Here we see that while China is still ahead, its lead is smaller. The US, Germany, and Japan fill the next places in the ranking, far ahead of all other countries. Switzerland remains in 9th place with 12 patents in hyperloop-related technologies and a Patent

Asset Index of 22. It is noteworthy that the number of patents from South Korea is the second highest, although its Patent Asset Index is relatively low. This indicates that the patents from South Korea are less often cited by other patents and market coverage is below average.

**Fig. 5-3 Top patent owners: broad definition**




Sources: Swiss Federal Institute of Intellectual Property, BAK Economics

Using this broad definition of hyperloop technology, Rockwell Automation reaches the top spot with 17 patents and a Patent Asset Index of 97. Virgin Hyperloop One and China Railway Construction are very close behind with a Patent Asset Index of 97 and 95, respectively. In terms of total patent numbers, the Chinese Southwest Jiaotong University, China Railway Construction and the Chinese CRRC Group have the largest patent portfolios.

Swiss ABB is in 4th place in terms of its Patent Asset Index value. ABB has 19 patents in hyperloop-related technologies such as its method for operating a long stator linear motor. However, most of ABB's patents were developed at the ABB subsidiary B&R in Austria.

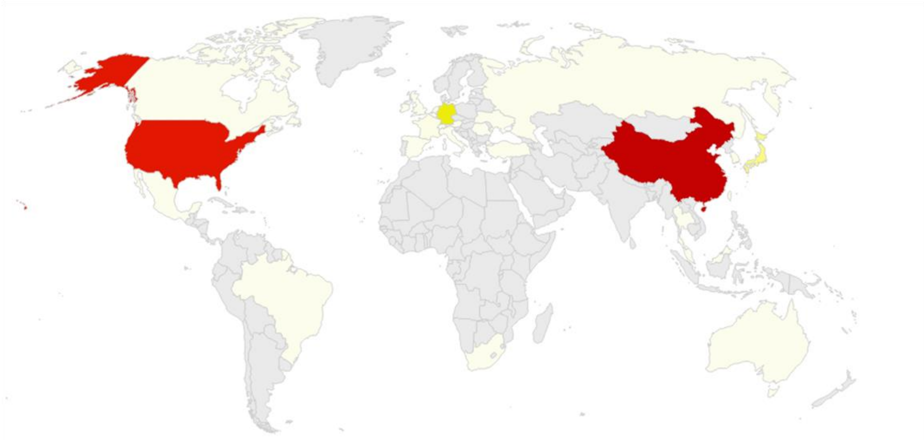
## 5.2 Patent analysis: Narrow definition

For the second definition, we only selected patents that include a direct connection to vacuum transportation, i.e., patents where the keywords "vacuum transport" are included in the patent descriptions. This narrow definition gives an overview of the technological know-how of companies or universities that are already pursuing the development of hyperloop.

In general, while the number of patents in the narrow definition of hyperloop is still relatively small, the results are comparable to the wide technology definition. Again, most patents were developed in China (239 patents), followed by South Korea (56), the US (55) and Japan (31).

According to the Patent Asset Index, China's lead is smaller with an index value of 236, compared to 203 in the USA and 62 in Germany. Switzerland is in 7th place with 5 vacuum transport patents and an overall Patent Asset Index of 9.

**Fig. 5-4 Top R&D locations: narrow definition**



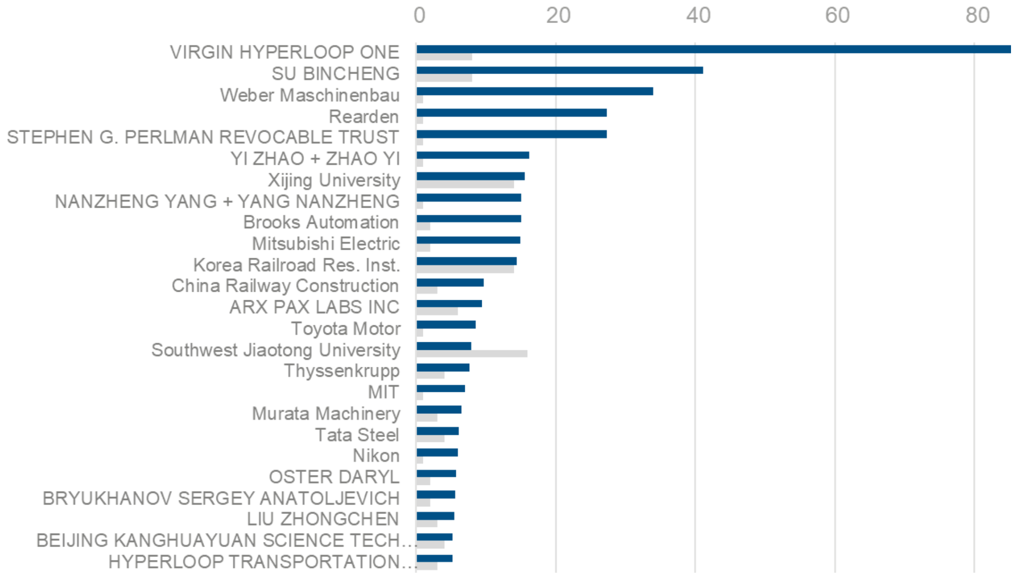
| | China | USA | Germany | Japan | South Korea | France | Switzerland | Australia | Canada | United Kingdom | Netherlands | Russia | Ireland | Austria | Mexico |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Patent Asset Index™ | 236 | 203 | 62 | 52 | 18 | 12 | 9 | 9 | 7 | 7 | 7 | 6 | 6 | 3 | 3 |
| Portfolio Size | 239 | 55 | 19 | 31 | 56 | 9 | 5 | 2 | 7 | 5 | 6 | 10 | 2 | 1 | 1 |

Sources: Swiss Federal Institute of Intellectual Property, BAK Economics

When looking at the top patent owners using the narrow definition, Virgin Hyperloop One reaches the top spot with 8 patents and a Patent Asset Index of 87. The Chinese inventor Su Bincheng also has 8 vacuum transport patents and a Patent Asset Index of more than 40. The Chinese universities Xijing University and Southwest Jiaotong University as well as the Korea Railroad Research Institute have the most hyperloop patents (each around 15 patents), but their Patent Asset Index is significantly lower. The hyperloop company Hyperloop Transportation Technologies ranks 25th with 3 patents and a Patent Asset Index of around 5.

There are no Swiss companies in the top 25 patent owners list yet. However, the Swiss transport research institute, a research institute founded by former ETH scientists who have ties to the Swissmetro organization, has two patents and the ETH and Cargo Sous Terrain both have one patent in this technology field.

**Fig. 5-5 Top patent owners: narrow definition**




Sources: Swiss Federal Institute of Intellectual Property, BAK Economics

## 5.3 Conclusion

The results of the patent analysis show that China and the US are in the lead concerning the protection of intellectual property rights in vactrain / hyperloop technologies.

China holds, by far, the most patents both in the broad definition of the technology (i.e., technologies related to hyperloop/vactrain such as maglev) and in the narrow definition of it (i.e., only patents that specifically cover hyperloop/vactrain). Chinese universities such as Chinese Southwest Jiaotong University and state-led companies such as China Railway Construction and the Chinese CRRC Group have large patent portfolios in these fields. However, the average valuation score of these Chinese patents is lower than those held in the US or Europe. Therefore, the US is close behind China in terms of the Patent Asset Index (which equals the number of patents multiplied by the average patent score).

Using the broad definition, the US and European countries are on relatively equal footing in terms of patent numbers and patent scores. There are also many patents from Japan and South Korea, but there, the average patent score is significantly lower than in Europe or in the US. Industrial companies such as Rockwell Automation, Siemens, or ABB hold many patents. ABB has 19 patents in hyperloop-related technologies such as a method for operating a long stator linear motor and is, therefore, in a good position to eventually become a technology supplier for hyperloop.

In the narrower definition, the number of patents is still relatively small which indicates that hyperloop / vactrain is still in its early stages of development. China and the US have the highest Patent Asset Index, followed by Germany, Japan and South Korea. On a patent owner level, Virgin Hyperloop One (VHO) takes the top spot in terms of the Patent Asset Index. Hyperloop Transportation Technologies (HTT) is also among the top 25 patent owners whereas there are no Swiss companies on this top list yet.

# 6 LinkAlong media analysis

The patent analysis in chapter 5 demonstrated that patent numbers in hyperloop technologies are still relatively small in total and that hardly any patents have been developed so far in Switzerland. That said, not all new inventions are patented. Some companies prefer to keep their inventions secret and not to publish their results in patent applications. Furthermore, smaller companies sometimes prefer not to patent in order to avoid patent fees. Universities also often do not patent their inventions. Therefore, it is important to also look at other indicators of innovation.

With this in mind, the analytical approach by the Swiss start-up LinkAlong[35] was used in order to analyze media coverage about hyperloop. The goal was to discover the companies and universities that are most often mentioned regarding hyperloop research.

The LinkAlong approach is based on the following steps. First, a list of relevant keywords (including hashtags) for hyperloop was created in an iterative process. Starting from an initial list ("hyperloop transport, vacuum tunnel, magnetic levitation," etc.), documents were collected and analyzed in order to identify all relevant keywords. These documents were found using Twitter's archive for the last two years and by following URLs in these specific tweets. Additionally, scientific publications were analyzed.

After a collection of documents was created in this way, the documents were classified with the help of concepts and topics, as well as user categories. Concepts are lists of keywords, possibly in different languages, that have the same or similar meaning. Such keywords were identified semi-automatically using semantic text analysis (simple neural networks) and manual data curation. Concepts were also grouped into categories with related concepts. Topics are combinations of concepts and categories. For longer documents (typically web documents), a document is only associated with a topic if the corresponding terms are mentioned frequently enough. User categories were created manually, using the metadata of the user accounts. As a result, the corresponding classified documents can be visually represented in various ways.

[35] LinkAlong is a solution enabling highly sensitive and domain-specific information filtering and aggregation to uncover highly valuable information hidden in massive information streams (https://linkalong.com)

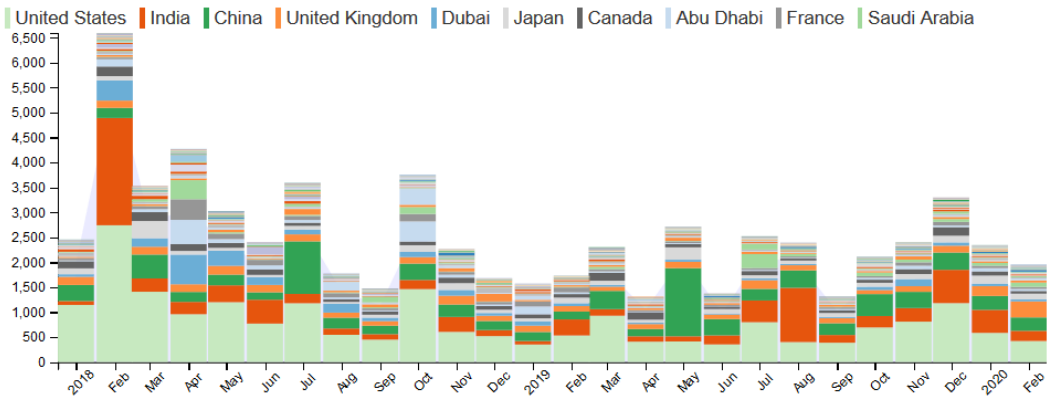
## 6.1 Top countries

The timeline results show that the US, India, and China were most often mentioned in media articles about hyperloop-related technologies and potential hyperloop (test) tracks in the last two years.

Three regions of the Middle East (Dubai, Abu Dhabi and Saudi Arabia) were also among the top 10 countries mentioned in terms of media coverage. This can be explained by the various planned projects for hyperloop tracks in the region.

Among the European countries, the UK occupies the clear pole position.

**Fig. 6-1 Timeline: top regions in terms of media coverage**

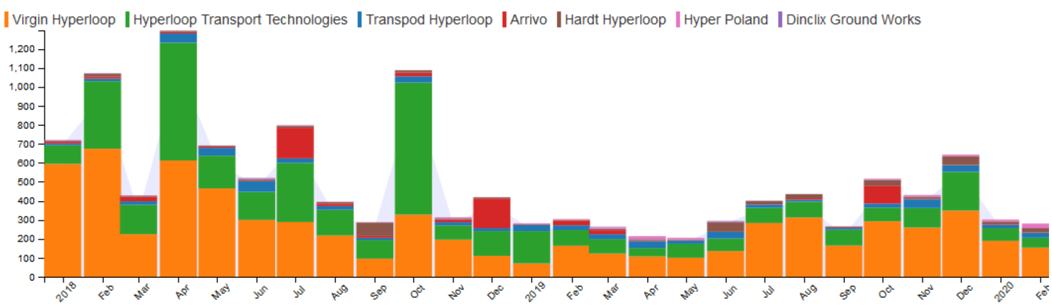



Source: LinkAlong

## 6.2 Top companies

Concerning hyperloop companies, most media articles since January 2018 have focused on two US companies: Virgin Hyperloop One and Hyperloop Transportation Technologies. Although the Canadian start-up Transpod Hyperloop reached third place and US Arrivo fourth, Arrivo has since shut down its activities due to lack of funding. Media reports spiked when Arrivo announced the shut down in December 2018 and in October 2019 when Hyperloop TT bought Arrivo's intellectual property. Hardt Hyperloop and Hyper Poland are most often mentioned among the hyperloop start-ups in Europe.

**Fig. 6-2 Timeline: top hyperloop companies in terms of media coverage**




Source: LinkAlong

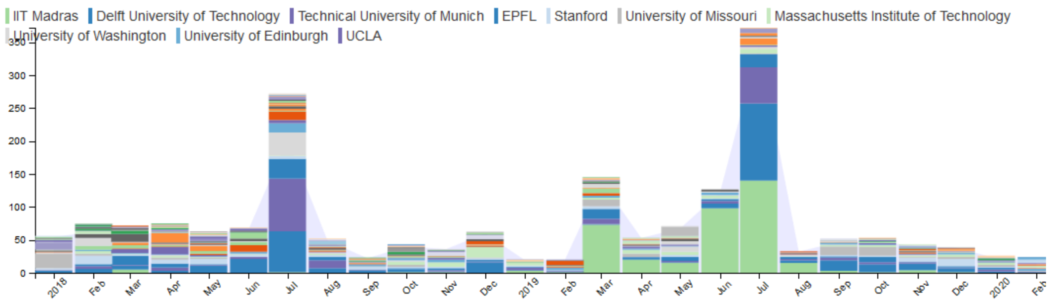
Apart from Indian DGWHyperloop (part of Dinclix Ground Works), no Asian hyperloop company is currently among the most often mentioned companies. A possible explanation for this is that vacuum transport research in China and Korea is driven by universities and research institutes such as Xijing University or Korea Railroad Research Institute (see also chapter 5).

## 6.3 Top universities

Figure 4-3 reveals the universities that have been mentioned most often in media articles covering hyperloop technologies since January 2018. However, it must be noted that this result is heavily influenced by the hyperloop pod competitions held by SpaceX in July 2018 and July 2019 as can be seen by the two resulting spikes in media coverage in these months. Therefore, most universities in this list have hyperloop teams that were participants in these competitions. This is an explanation why the Chinese universities do not appear in this list.

The Indian IIT Madras, the Delft University of Technology and the Technical University of Munich occupy the top three spots in terms of media coverage and Swiss EPFL is close behind in fourth. The Swiss ETH is not among the top 10 universities in terms of coverage since January 2018, but it is only slightly behind UCLA which ranks 10th. The student teams of EPFL and ETH had very good results in previous hyperloop pod competitions (ETH: second place 2019, third place 2017, EPFL: third place 2019, third place 2018).

**Fig. 6-3 Timeline: top hyperloop universities in terms of media coverage**



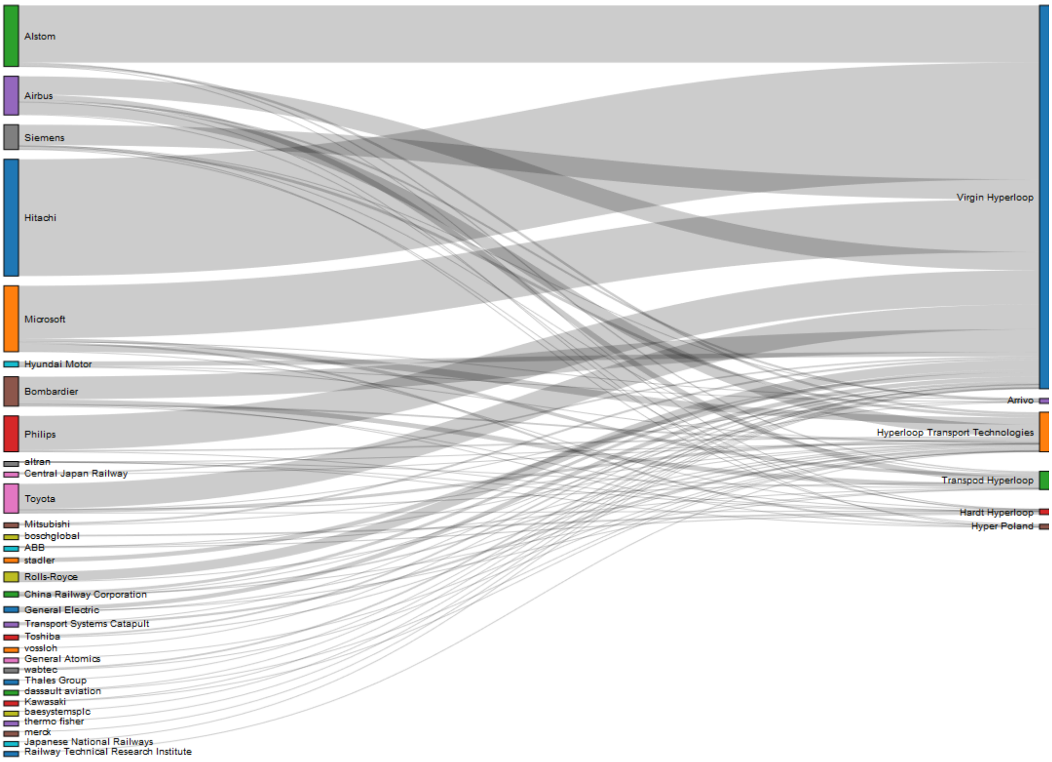

Source: LinkAlong

## 6.4 Linkages between companies

Figure 4-4 shows how often hyperloop companies have been mentioned together with other companies in media articles since January 2018. These citations together can be an indicator of cooperation between the mentioned companies, but they can also imply competition or other reasons.

Again, Virgin Hyperloop One (VHO) is clearly ahead of all other hyperloop companies. An explanation for the numerous citations of VHO with established industrial companies is that VHO has already partnered with companies such as SNCF, GE or Deutsche Bahn. Hyperloop Transportation Technologies and Transpod Hyperloop have the second and third most linkages with other companies in terms of mentions in media articles. Swiss ABB has recently been mentioned in conjunction with Hardt Hyperloop in the media because ABB is now collaborating with the Dutch start-up.

**Fig. 6-4 Media linkages between companies**




Source: LinkAlong

## 6.5 Conclusion

The results from the LinkAlong media analysis show that hyperloop has been a frequent topic in various press articles since January 2018. On a country level, the US, India and China have been mentioned most often regarding hyperloop-related technologies and potential hyperloop (test) tracks.

On a company level, Virgin Hyperloop One and Hyperloop Transport Technologies clearly dominate the press coverage. These two companies are mentioned far more often than all other hyperloop companies combined. Virgin Hyperloop One is also the clear leader in terms of articles where hyperloop companies and established industrial companies are cited together. This is an indicator that Virgin Hyperloop One has already partnered up with many large industrial companies.

Most universities that have been in the media related to hyperloop were participants in the hyperloop pod competitions in 2018 and 2019. The Indian IIT Madras, the Delft University of Technology and the Technical University of Munich hold the top three spots and Swiss EPFL is close behind in fourth. Both EPFL and ETH have achieved very good results in the previous hyperloop pod competitions. This shows that Switzerland is among the top countries in terms of university research in hyperloop.

# 7 Expert Interviews

In order to obtain a comprehensive picture of the advantages and disadvantages of hyperloop as well as the remaining challenges and the chances of the EuroTube project proposal, BAK held several open interviews with selected experts. The results of these interviews are summarized in this chapter

## 7.1 Mario Paolone

Professor Mario Paolone is a professor at the Swiss Federal Institute of Technology in Lausanne (EPFL), where he is Chair of the Distributed Electrical Systems Laboratory and Head of the Swiss Competence Center for Energy Research. He was also the academic advisor of the EPFLoop team who participated in the SpaceX hyperloop 2018 and 2019 competitions.

According to Professor Paolone, there are two main challenges before Hyperloop could become a feasible transport option in Europe. First, tunneling costs must decrease and second, specific safety questions need to be solved.

Regarding tunneling costs, Professor Paolone pointed out that the Elon Musk-led Boring company is mainly focused on developing technologies capable to largely decrease tunneling costs. If the Boring Company achieves this target, hyperloop routes will probably become competitive with respect to established transport options such as rail and planes even in countries such as Switzerland. Future hyperloop tracks should be connected to transport hubs such as large train stations or airports. However, he thinks that the first commercial track is likely to be constructed in the Middle East by Virgin Hyperloop One.

Important safety problems are linked to the vacuum in the tubes. In the case of accidents, the need for the isolation of the tunnel section where a capsule is stopped, the tunnel re-pressurization and speedy evacuation, poses difficult tasks for the design of the hyperloop tracks, according to Professor Paolone. Another challenge is posed by the capsules operation with respect to the heat dissipation in vacuum.

Concerning technology developments, Professor Paolone mentioned that many research activities currently focus on the development of vehicles that are energy-autonomous with the (desirable) consequence to have an energy-passive rail. This should offer cost advantages compared to electrified tracks that are used, for instance, in Transrapid maglev trains. For the capsule propulsion, Professor Paolone thinks that electromagnetic linear motors are the most promising in view of their simplicity and robustness.

Moreover, the EPFL has developed advanced control systems and sensors that can estimate the location of the pods precisely and are resilient against the loss of information coming from multiple sensors. Professor Paolone argues that control systems will be easier to optimize for hyperloop compared to other transport systems because hyperloop pods will operate only in one-way traffic with no obstacles created by other forms of traffic.

Professor Paolone also thinks that the level of cyber-security will be higher in a hyperloop system since new hyperloop tracks will be built from scratch meaning it should be possible to provide and install software updates for hyperloop via online downloads similar to software updates in current Tesla cars.

According to Professor Paolone, the implementation of 5G will facilitate hyperloop communication systems due to the inherent time-determinism of this telecom infrastructure.

When asked about the planned test track of EuroTube in Switzerland, Professor Paolone replied that we are still in a research stage and he prefers the design of the soon to be built reduced scale hyperloop vacuum test track at the EPFL. The EPFL test track will be a circular one with a 45-meter diameter with a 1:10 scale. The main advantage of a circular track is that the pods can run for a longer time than in a linear short track. According to Professor Paolone, this provides a more realistic test setting to study the pod levitation system, its propulsion as well as study various geometry to the rail. All these elements are more difficult to study on a linear test track with limited length where pods cannot accelerate up to their cruising speed since they, shortly after their launch, need to slow down. However, the top speed at the EPFL test track will be lower than in the proposed EuroTube test track due to its small scale and circular shape. However, it will reproduce the same energy needs per-unit mass of the full-scale capsule.

Regarding the business opportunities for Swiss companies in hyperloop, Professor Paolone thinks that Switzerland has good prospects in the fields associated to the engineering of the capsule propulsion and levitation systems.

## 7.2 Thomas Sauter-Servaes

The second expert interview was conducted with Dr Sauter-Servaes from the Zurich University of Applied Sciences (ZHAW). Dr Sauter-Servaes works at the ZHAW in the Department of Applied Mathematics, Physics, Systems and Operations. He is also a founding member of a think tank, Denkfabrik Mobilität, a member of the Board of Directors at the organization Intelligent Transport Systems Switzerland and a publisher of Eurailpress.

Dr Sauter-Servaes is skeptical about the promised reduction of greenhouse gas emissions by hyperloop. While hyperloop connections would likely be more energy-efficient per passenger compared to established transport means, hyperloop would increase overall traffic even further. This increase in induced demand would probably lead to even higher emissions. Therefore, he thinks hyperloop is not the adequate transport option to reach the climate targets set for reducing greenhouse gas emissions in the EU.

According to Dr Sauter-Servaes political obstacles are another problem regarding hyperloop. Because a hyperloop would increase the accessibility and attractiveness of connected cities, there would be fierce competition between regions over where the first hyperloop tracks would be built.

Moreover, Dr Sauter-Servaes argues that hyperloop would be most attractive in Europe for connecting cities in different countries. Therefore, cooperation and standardization between countries would be necessary throughout Europe which would be difficult to achieve.

Another disadvantage of hyperloop is that new connections would be very expensive and would most likely require large public investments. Therefore, high opportunity costs exist since governments could also allocate these same funds to improve their existing transport systems. Many countries have, for example, already invested heavily in their rail systems, therefore, Dr Sauter-Servaes questions whether these countries would be willing to invest significantly in a competing technology.

In summary, Dr Sauter-Servaes does not believe that hyperloop connections will be built in Europe in the foreseeable future. However, he thinks that hyperloop has better prospects in Asia where it could, for example, be built to connect cities without existing train connections.

## 7.3 Marcel Jufer

Marcel Jufer is a Professor Emeritus at the EPFL. He was also the scientific coordinator of the Swissmetro project from 1989 to 2007 and since 2010, he is in charge of the Swissmetro know-how and valorization for the EPFL.

First, the similarities and differences between the Swissmetro project and new hyperloop concepts were discussed in the interview. According to Professor Jufer, Swissmetro and hyperloop share many similarities, but there are two key differences. The first difference is that a Swissmetro connection would be completely underground instead of in tubes on pillars for hyperloop. Second, Swissmetro would be slower than hyperloop with a top speed of around 500 km/h versus 1,200 km/h for hyperloop.

Professor Jufer argues that tunnel connections have significant advantages. Tunnels are easier to build within a city. There is no noise and a much lower risk of sabotage or terror attacks because Swissmetro's underground tracks would be impossible to access.

Regarding the lower top speed, Professor Jufer explains that Swissmetro's main goal is to connect Swiss cities. Therefore, the distances between destinations are much shorter than for most planned hyperloop connections. In order to connect Swiss cities, lower speeds are favorable because less power is required for acceleration and deceleration. Consequently, Swissmetro would be more energy-efficient than hyperloop for short Swiss connections. However, in general, Professor Jufer argues that vacuum transport is a promising transport option for both short and medium distances.

One advantage of hyperloop is that most hyperloop companies plan to build relatively small pods that can be powered by batteries and can move autonomously. The Swissmetro design shares a similar concept with the Transrapid and its active powered track and is, therefore, more expensive to build according to Professor Jufer.

Regarding safety questions related to the vacuum in the tubes/tunnels, Professor Jufer is convinced that safety can be ensured. The Swissmetro design includes small additional tubes in the vacuum tunnels that could help to repressurize and provide air quickly in the case of an accident.

Concerning the commercial outlook for vacuum transportation, Professor Jufer thinks that the first commercial hyperloop tracks will likely be built in the Middle East within the next 10 years. In Switzerland, it will take longer and around 20 years is a more realistic time frame. The cost of vacuum tube tunnels is the main obstacle in Switzerland. However, Professor Jufer notes that new railway lines are also expensive and complicated to build and tunnels for hyperloop and Swissmetro can be built with a much smaller diameter than train tunnels. It might also be an option to combine a hyperloop or Swissmetro connection with a cargo transport system such as Cargo sous Terrain. For example, the tunnels could be used for high-speed transport of passengers during the day and for cargo transport at night.

Professor Jufer also believes that some Swiss companies are in a good position to become suppliers for vacuum transport systems in the future. He mentioned ABB as a supplier for battery-charging systems and VAT Group as a potential vacuum tech supplier.

When asked about the necessity for a vacuum transport test track in Switzerland, Professor Jufer replied that a test track would have advantages for the research landscape. However, he is uncertain of the commercial benefits of such a project as there will be competition from other test tracks that are currently being built in Europe.

## 7.4 Carl Brockmeyer

Carl Brockmeyer is currently the President of the Scientific Vacuum Division at the Swedish industrial company Atlas Copco, which bought vacuum specialist Leybold in 2016. Leybold is a vacuum tech supplier for several top hyperloop companies.

Mr Brockmeyer is of the opinion that many relevant technologies for hyperloop are already well-developed and manageable. While technological challenges exist, he is optimistic that these challenges can be solved in the future through research and testing. Therefore, the high cost of hyperloop tracks is the main obstacle in his view. The construction of a hyperloop track would likely require significant public investment. Given this, Mr Brockmeyer believes that the probability for the construction of a first commercial hyperloop connection is higher in the Middle East than in Europe because the need for new infrastructure is more urgent in the Middle East and financial and geographical conditions are better.

A major part of the interview focused on the vacuum technologies that are essential for hyperloop. Mr Brockmeyer is convinced that it should be technologically feasible to create and maintain a vacuum in the planned commercial hyperloop routes. Essentially, long tracks require a higher quantity of vacuum pumps, valves etc. compared to a shorter track. Despite these necessary higher quantities of vacuum equipment, he believes that the vacuum will only be a relatively modest factor in the overall cost of hyperloop connections. He explains that the vacuum systems will require energy mainly to initially create the vacuum. In regular operation mode, the energy usage should be low because vacuum pumps only need to compensate for small natural leakages from the valves, airlock chambers, etc.

Mr Brockmeyer believes that the main cost driver of hyperloop will be the initial construction of the tubes/tunnels. He adds that there is a trade-off between the quality of the tube and the costs for the vacuum pumps and valves. High quality materials for the tube will reduce natural leakages and lower vacuum costs, but also increase initial construction costs.

Concerning the much-debated safety questions related to the vacuum in the tubes, Mr Brockmeyer states that it is important to take safety concerns seriously. However, he is optimistic that the main safety problems such as the possibility of an evacuation in case of accidents can be solved eventually by the hyperloop companies and the technology suppliers. He points out that other transport options such as planes also have significant safety problems, i.e., it is impossible to evacuate an airplane in flight. Mr Brockmeyer also mentions that insurer Munich RE conducted a study in 2019 that showed that hyperloop routes can be insured.

Regarding the commercial prospects of Swiss companies in the hyperloop field, Mr Brockmeyer thinks that there should be many opportunities for Swiss companies as technology suppliers since there are many successful and innovative Swiss mechanical engineering companies. He mentions VAT Group as a potential beneficiary of hyperloop since VAT Group already supplies some hyperloop companies with vacuum tech.

## 7.5 Jörg Jermann

Jörg Jermann is a Senior Consultant of Rapp Trans, a Swiss transport consultancy.

The first topic of the interview with Mr Jermann was the Swissmetro concept. According to Mr Jermann, there are two main factors that have prevented the construction of Swissmetro connections in Switzerland: First, the advantage of point-to-point connections is less beneficial in Switzerland than in other countries because many people live in areas between cities. Therefore, the time advantage of Swissmetro compared to other transport options is limited for people who still need to travel from rural or suburban destinations. The second reason against Swissmetro is the high cost for the construction of the tunnels. To recuperate these costs, high ticket prices would be necessary thus limiting demand.

Mr Jermann thinks that the medium to long distances that are planned for hyperloop connections are more suitable for vacuum transport because at these longer distances, the speed advantage of vacuum transport becomes more relevant. However, he notes that the implementation of hyperloop will be complicated on a political level. As most planned tracks in Europe would be international connections, countries, regions and cities all would have to agree on a track route leading to competition over where the first hyperloop tracks would be built.

Therefore, Mr Jermann thinks that it will take several decades before hyperloop becomes part of the transport systems in Europe. However, there might be some prestigious point-to-point connections such as Paris to London, where a hyperloop track could be built earlier.

Mr Jermann also stated that the use of tubes is better than regular train tracks because the land underneath the tubes can still be used for other purposes. Therefore, the acquisition of land for tubes should be less costly. In cities, he is convinced that a hyperloop tube above the ground is preferable to tunnels because access time would be reduced. He suggested that the elevated tubes could be built on top of existing train tracks.

According to Mr Jermann, it is important that hyperloop connections go to the city center so that hyperloop avoids one major disadvantage of air travel. In general, Mr Jermann thinks that new hyperloop connections should mainly compete with air travel and should be integrated into the existing rail network for further connections to final destinations. To increase the likelihood of the commercial success of hyperloop, companies should try to market hyperloop by focusing on the benefits for passengers, instead of focusing on technology.

Mr Jermann noted that hyperloop could possibly also compete with air travel concerning cargo transport, but it is debatable if there would be enough demand. Hyperloop stations could be built next to ports and the tubes could be used for cargo transport at night when there is less demand for passenger traffic.

Mr Jermann agreed with the assessment of Dr Sauter-Servaes regarding induced demand. The speed advantage of hyperloop compared to existing transport options would create new traffic. Second-round effects are also to be expected, for example, effects on real estate markets.

Regarding the opportunities for Swiss companies, Mr Jermann argued that Switzerland is competent in the implementation and operation of complex transport systems. This might lead to opportunities for Swiss companies even if hyperloop connections are only built outside Switzerland. Civil engineering and control systems/software are particularly promising areas for Swiss companies.

## 7.6 Yvette Körber

The last expert interview was conducted with Yvette Körber. Ms Körber is the CEO of Amberg Loglay AG. Ms Körber is also a managing partner at CargoTube and a member of the board of directors of Cargo Sous Terrain.

Ms Körber is very skeptical about the commercial prospects of hyperloop in Switzerland. She does not believe that commercial routes in Switzerland will be built. Hyperloop will face similar obstacles as Swissmetro. First, tunnel costs are prohibitively high. While tunnel construction costs are likely to decrease somewhat in the future, these cost reductions will not likely be enough to make hyperloop tunnels competitive in Switzerland. The large amount of excavation during tunneling work would pose an additional challenge. Second, relatively short point-to-point connections such as Zurich to Bern are unrealistic because the time saved would only be limited for many people who would still need to travel to their final rural destinations.

In addition, Ms Körber also believes that longer hyperloop connections from Swiss cities to European cities are unrealistic. The political implementation would be highly complicated because different countries, regions and cities would have to agree on a commercial track. Moreover, it would be very difficult to get building permits for a long track. These various uncertainties will discourage potential investors according to Ms Körber.

However, Ms Körber sees potential for a small number of point-to-point vacuum transport connections in the Middle East, India, China, the US and maybe from Finland to Sweden (Helsinki to Stockholm). However, an extended hyperloop network is unlikely because construction costs would be too high compared to air travel.

Nevertheless, Ms Körber thinks that there are good prospects for Swiss companies to become suppliers for foreign hyperloop tracks in areas such as mechatronics, vacuum tech, ventilation, and tunnel construction.

Concerning the planned test track and research center of EuroTube in Switzerland, Ms Körber sees only limited chances of success. Several test tracks are going to be built in Europe in the coming years, even though only one or two test centers will likely become relevant in the end. According to Ms Körber, the chances for the EuroTube project to become the leading test center in Europe are small. She thinks that the open research concept in Switzerland with many different contributors is unlikely to generate a hyperloop standard that will be adopted in Europe. Other planned test tracks have a key player as a driving force such as Hardt Hyperloop in the Netherlands or Hyperloop TT in France and Ms. Körber thinks that this is a more promising concept. Moreover, she believes that the Dutch hyperloop company Hardt is in a better position to earn the support of the EU than EuroTube.

## 7.7 Conclusion

The interviews make clear that there is overall agreement among experts in their assessments of several questions related to hyperloop/vactrains. First, most interviewees think that the remaining technological challenges of hyperloop can be solved in the (near) future.

Second, all experts agree the high cost of the construction of the tracks and, in particular, of tunneling are major obstacles. In fact, most interviewees predict that the first commercial hyperloop tracks will be built in the Middle East or Asia where certain requirements (such as fewer necessary tunnels and less train infrastructure) will be more easily met than in Europe.

Finally, the interviewees stated that Swiss companies are in a good position to become technology suppliers for eventual hyperloop tracks in various fields such as power electronics or vacuum tech.

Naturally, however, there are also some assessments that differ. For example, some experts think that safety issues related to the vacuum required are a key problem, whereas other experts are optimistic that vacuum technology for the tubes/tunnels is already well-developed and that safety issues can be solved soon.

Concerning suitable track lengths for hyperloop, most experts argue that medium distances (between 300 and 1400 km) are ideal because, for shorter distances, the speed advantage of hyperloop compared to high-speed rail is too minor. Although only one expert thinks that vacuum transportation is also a good option for short distances, all experts agree that for long distances, construction costs would become too high for hyperloop to compete with air travel.

There are also differing assessments regarding the impact of hyperloop on greenhouse gas emissions. Several experts expect that the implementation of hyperloop would reduce greenhouse gas emissions in the transport sector due to the higher energy efficiency of hyperloop compared to other transport means. However, two experts argue that hyperloop will lead to a rise in induced demand for transportation and this effect could even cause emissions to increase.

Finally, some experts predict that a commercial hyperloop track will be built in Switzerland in around 20 years while others think it will take around 40 years. One expert is convinced that hyperloop tracks will never be built in Switzerland.

# 8 Opportunities and risks of the Eurotube Project

The EuroTube Foundation is a Swiss foundation and non-profit research institute that plans to build a vacuum transportation test center in Collombey-Muraz in the Canton of Valais. According to EuroTube, the main goals are to build and operate test infrastructures for high-speed vacuum transportation, to generate knowledge and to enable technology transfer for public use. EuroTube wants to offer their planned test infrastructures for universities and companies and provide material and immaterial support to research projects in order to encourage the necessary breakthroughs in vacuum transport solutions.

EuroTube has three main research priorities that it will focus on in the coming years. First, the development of an innovative tube material made of textile reinforced concrete that is assumed will reduce leakages from the vacuum tubes. This project is being developed in conjunction with Creabeton Matériaux and other partners. Second, research activities will focus on the development of linear motors. EuroTube is researching the technical and economic feasibility of high temperature superconductor (HTS) linear motors compared to conventional linear motors. Another important research topic is the development of vacuum valves in cooperation with VAT Group and inspire AG.

The planned test center in Collombey-Muraz consists of several parts. The most important first step is the construction of a three-kilometer-long and 2.2-meter-wide test track called AlphaTube. EuroTube plans to complete this first track by 2022. In the longer term, a second test track with a length of more than 30 km (called BetaTube) is to be built.

However, as a non-profit research organisation, the EuroTube Foundation depends on funding and donations and has requested public funding from the federal government in order to build the first test track.

## 8.1 Opportunities

The results of the previous chapters have shown that vacuum transportation technology is still in the early stages of development. While both some hyperloop companies such as Virgin Hyperloop One and some Chinese universities appear to have a technological lead in certain areas, it should still be possible to create a vacuum transport technology cluster in Europe that can compete with its American and Asian rivals. A key prerequisite for this is to have an adequate test track that enables universities and companies to test and further develop their technology solutions.

The planned AlphaTube test track from EuroTube would be larger than all currently existing test tracks (see chapter 4.3.1). Its dimensions would allow pods to reach a speed range between 700 and 900 km per hour – a clear improvement over currently available test tracks.

In particular, the research focus on textile reinforced concrete appears promising, because EuroTube hopes that its concrete technologies will be significantly cheaper than steel pipes. If EuroTube achieves these cost reductions, it would have an advantage over competitors since high construction costs for vacuum transportation tracks are a major obstacle.

Moreover, EuroTube's test center will differ from other test tracks that are currently being planned around the globe. While most other test centers are spearheaded by private, venture-backed companies such as Virgin Hyperloop One that offer limited accessibility to other companies, EuroTube is committed to opening its test center to all universities and companies and aims to make its research results publicly available through open-source publications. Given this transparency, the new EuroTube test track should create a test setting that is attractive to various entities. In fact, EuroTube already cooperates with the Swiss universities ETH Zurich and EPFL, the German university RWTH Aachen as well as with several industrial partners.

In Europe, the implementation of commercial hyperloop systems will require new standards and legislation that enable hyperloop to be integrated into existing transport infrastructure systems. Thus, a test center in Switzerland would likely be in a better position to develop vacuum transport solutions for the European market compared to US or Asian rivals. In the US and Asia point-to-point hyperloop connections are more likely since the rail networks are less well-developed in many regions there.

Another advantage of the EuroTube project is that there has already been a long tradition of vacuum research in Switzerland thanks to the Swissmetro project. The excellent capabilities of both ETH and EPFL in hyperloop technologies, as demonstrated in recent hyperloop pod competitions, reflect this longstanding know-how. The EuroTube test track could improve the Swiss innovation system further by generating knowledge spillovers between universities and companies that improve competitiveness. Thus, the test track could help ensure that Swiss universities remain at the forefront of vacuum transport research. Research programs at EPFL and ETH would, in turn, guarantee an abundant supply of skilled experts from Switzerland who could work for hyperloop technology companies in the future.

One promising fact regarding the location of a vacuum transport research center in Switzerland is that there are already several Swiss companies active in relevant technologies that have also cooperated with the hyperloop student teams of EPFL and ETH. Vacuum transport could offer new business opportunities for these companies. Some examples include:

- Power electronics and energy solutions: ABB
- Sensors: Baumer
- Vacuum Technology: VAT Group
- Tube materials: Creabeton
- Pod materials: Gurit, Connova Group, GF Casting Solutions
- Linear motors: Brusa, Valélectric Farner SA, Gebrüder Meier AG
- Brakes: Furka Reibbeläge AG

- Components: Stäubli International
- Energy Solutions: LEMO, Leclanché AG
- Transport systems competence: SBB

Some of these companies such as ABB and VAT Group are world-leaders in their respective areas and are likely to succeed as hyperloop suppliers even without a test track in Switzerland. However, this proposed test track could help smaller companies with fewer financial resources to develop their products and benefit from a possible commercial hyperloop breakthrough.

If the EuroTube test center is a success and becomes a leading global vacuum transport research cluster, it would lead to significant value creation in Switzerland. The research center could lay the foundation for a new industry that would create numerous high-skilled jobs in Switzerland, lead to the emergence of new businesses, build up national and international networks, and cause significant knowledge spillovers. EuroTube and Swiss Companies may eventually secure this knowledge with intellectual property rights. This could enable Swiss companies and start-ups to capitalize on the knowledge and expertise gained in the test phase when the companies involved eventually construct a hyperloop for commercial purposes.

## 8.2 Risks

A major risk associated with EuroTube's planned test center is the competition that could arise from other planned test centers in Europe. While EuroTube's test track AlphaTube is projected to be one of the longest test tracks available once open, there will be several competing test tracks that will probably open at around the same time or shortly thereafter. Therefore, there will be a lot of competition from other test sites around the globe. For example, the planned test center by Hardt Hyperloop in the Netherlands could become a key competitor in Europe as Hardt Hyperloop has a relatively similar approach that is also based on cooperation with many industrial partners.

EuroTube expects that its test site will not only be in high demand by Swiss universities but also by other universities and companies. However, if Hardt Hyperloop or other test centers such as the ones from Virgin Hyperloop One see more rapid technological progress, leading universities and companies may prefer to test their solutions at these locations. It is unlikely that, in the end, there will be many regions with hyperloop clusters, rather, only two or three regions will probably emerge as leaders. While EuroTube's project has good prerequisites, it is by no means guaranteed that EuroTube will become a leading hyperloop cluster in the end.

On a positive note, there are also advantages to having several competing test centers. The competition will most likely lead to developing better and faster technology in vacuum transport technologies.

The second major risk is that the remaining technological obstacles to vacuum transport cannot be solved in the coming years or that advances in competing technologies such as sub-orbital flights make hyperloop obsolete. In this case, the investment in EuroTube's research center might not lead to any commercial applications in the end.

## 8.3 Conclusion

The EuroTube project could generate significant value creation in Switzerland if its research site in the canton of Valais succeeds and becomes a leading global technology cluster. However, there will be tough competition between different research sites in the coming years.

Given the excellent research capabilities of Swiss universities in vacuum transport technologies and the numerous companies that are already active in related technologies, EuroTube is in a good starting position. Nevertheless, it is not guaranteed that EuroTube can keep up with its numerous rivals from the US, Asia, and Europe. Furthermore, it remains to be seen whether or not the remaining technological hurdles to the commercialization of hyperloop can be surmounted and construction costs can eventually be decreased.

All in all, the EuroTube research project is, therefore, a high-risk, high-reward project. Given the relatively manageable amount of public funding that is needed to initiate the construction of the first test track, we think that it would be the right decision to fund EuroTube now in order to boost the chances to get the testing and further development of hyperloop / vactrains to Switzerland. However, it will be important to closely monitor EuroTube's technological progress compared to its competitors in the coming years.

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