Scope of this knowledge search

As a quick knowledge search, this report provides key bibliographical references and limited analysis. It is intended to inform decisions about the scope and direction of possible research and innovation initiatives to be undertaken in this area. It does not provide definitive answers on this issue; and is not intended to represent RSSB’s view on it.

The search may only include what is available in the public domain.

It has been conducted by a team with expertise in gathering, structuring, analysing both qualitative and quantitative information, not by specialists in the field. Experts in railway operations or other personnel in RSSB, or elsewhere, may not have been consulted due to the limited time available. Industry and experts in this field are very welcome to make observations and to provide additional information. Please send comments to knowledgesearch@rssb.co.uk.

For further information or background to this report, please contact RSSB Knowledge Management and Systems at knowledgesearch@rssb.co.uk.
Executive Summary

This knowledge search was undertaken on behalf of the RSSB Innovation team, to see what information is available in the public domain on the hyperloop concept, technologies and business model.

The Hyperloop concept was made popular by Elon Musk, CEO of SpaceX, in a 2013 communication. In a white paper entitled ‘Hyperloop Alpha’, Elon Musk described the concept of a near supersonic, fixed-guideway, intercity transportation system which would disrupt passenger and freight transport in the near future. The idea stems from the pneumatic tube based vactrain concept (1909), and from other ideas and technologies developed by SpaceX.

The Hyperloop was advertised as a system capable of shuttling passengers or cargoes between cities in much less time than a modern commercial aircraft (with a speed of 1200 km/h or 760 mph) due to the minimisation of friction and air resistance, using lower power consumption than traditional high speed rail, and being fully automated, collision free, and immune to weather.

SpaceX developed the first proof-of-concepts and launched public competitions for testing their designs, and commercial ventures have more recently started developing the needed technologies, like Hyperloop One, Hyperloop Transportation Technologies (HTT) and Transpod.

Many governments (in India, Dubai, Russia, the People’s Republic of China, South Korea, USA) have commanded feasibility studies on the Hyperloop, demonstrating their growing interest in the subject. San Francisco – Los Angeles, Helsinki – Stockholm, Dubai – Abu Dhabi, Vienna – Bratislava – Budapest, and Toronto – Montreal have been proposed as the first hyperloop routes to be deployed.

This report aims at providing a high-level evaluation of the Hyperloop in terms of its technological advancement, commercial potential, costs, and remaining safety issues.

The individual technologies on which the hyperloop concept rely (partially evacuated tubes, passive maglev, linear induction motors, regenerative breaking) are to some extent already established technologies, or have been demonstrated to be successful in recent trials. However, this knowledge search found no evidence of these technologies having been successfully integrated on a wide scale system level. As a result, the announced dates for the deployment of the first hyperloop routes (2020) seem to be over optimistic.

The main value proposition of Hyperloop (and its main disruptive characteristic) is to offer high speed transport at a cheaper cost than high speed rail and commercial airlines, due to lower investment costs (lighter infrastructure, less land usage and civil engineering work) and lower operational costs (full automation, lower power consumption, local energy production and storage). However, our research and analysis shows that the announced construction and operational costs are likely to have been underestimated by a factor of 2 to 3 at minimum. For instance, whereas the initial Musk proposal for the San
Francisco/Los Angeles route mentioned investment costs of $54 million for the pods and $650 million for the tube infrastructure, a more recent estimate published in the Ivey Business Review gives respective figures for the pods and the tubes in the range of $147 - 159 million and $1,650 - 2,480 million.

It was also found that the maximum annual capacity of the Hyperloop is likely to be half that of High Speed Rail. Although it is 2-3 times more fuel efficient than rail, it offers less interoperability because of the partially vacuumed operating conditions.

Finally, there remain many unaddressed engineering and safety issues, that hinder the chances of a passenger Hyperloop system being ready for deployment in the next decade. For instance, it is unclear how the system will deal with heat dissipation in an ambient pressure around 1/1000 of the atmospheric one, with capsules running at 760mph.

Thermal expansion of the tube, which could reach 300 meters on a 560km of route in California (with a temperature differential of 50°C), has likewise not been given a credible mitigation solution in the available Hyperloop proposal.

The business model of the hyperloop relies on a very close proximity of the travelling capsules, which causes many safety concerns in case of system failure. The traveling pod has, at around 760 mph, a kinetic energy of just over 3 million joules, which is equivalent to the energy of 75 to 200 kilograms of exploding TNT (depending on the size of the pods and passenger numbers). With no way of dissipating that energy in the advent of an accident (in contrast to aircrafts), the hyperloop cannot pass through residential or urban areas without becoming a great safety concern.
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1 HYPERLOOP: ORIGIN AND CONCEPT

1.1 ORIGIN
In 2013, the CEO of SpaceX, Elon Musk, released a white paper entitled ‘Hyperloop Alpha’, which included the business case, preliminary costings, line plan and an overview of the technology. It was proposed that a track would run from Los Angeles to San Francisco, reducing the journey time to 35 minutes, compared to 1 hour and 30 minutes by aircraft. The frictionless conceptual design was in fact iterated several times before Elon Musk’s proposal in 2013. The idea of pushing railway carriages with forced air has been around since the early 1800s, but technological limitations made the economics of the then called “atmospheric railway” unjustified. Developments in high-speed rail have historically been impeded by the difficulties in managing friction and air resistance, both of which become substantial when vehicles approach high speeds. To this day, the Hyperloop technology is still unproven, but it has elicited a great deal of interest from journalists, investors, engineering firms, and governments.

1.2 CONCEPT
The Hyperloop is a concept for a near supersonic, fixed-guideway, intercity transportation system. It is akin to rail transportation, but uses capsule-like windowless carriages (instead of wagons) that operate in sealed partial-vacuum tubes instead of rail tracks. The capsules, also called pods, have an aerodynamic fuselage and structure, and are expected to shuttle passengers or cargo between cities in less time than a modern commercial aircraft. The system is estimated to have several pods travelling close to one another at a maximum speed of around 1200 km/h (or 760 mph).

Musk initially proposed that pressurised pods would levitate on an air cushion driven by linear induction motors (LIMs) and air compressors. However, current design proposals seem to focus on using passive magnetic levitation instead of an air levitation system. The pods would travel in a partially evacuated tube (= 1/1000 of normal atmospheric pressure) with a substantially larger diameter than the carriages themselves.

1.3 ADVERTISED BENEFITS: HYPERLOOP AS A DISRUPTOR
Hyperloop has been coined as the 5th mode of transport and is a direct competitor to the rail industry. The technology has gathered a lot of attention from profit-minded companies because it claims:

- to have practically zero net emissions

- to be near-supersonic with extremely short transit time (35 minutes, compared to 1 hour and 30 minutes by aircraft for the same route) which would revolutionise intercity travel.
- to have low construction costs (only 10% of HSR construction cost according to Musk, 40-60% of HSR construction cost according to the commercial ventures) as it will have a lighter infrastructure and minimum land usage.

- to be relatively cheap in terms of ticket prices, $20-30 for the L.A. to San Francisco route whereas the California High Speed Rail (under construction) would have a ticket price of $86 for the same route.

- to require only 1/3 of the energy of air travel on a passenger mile basis; 2-3 times more fuel efficient than rail

- to be more resilient to external environmental factors than other means of transport as the pods are enclosed in a pressurised tube.

- to be fully automated, hence no human error.

## 2 Tests and Development

### 2.1 Early Tests and Pod Competitions

On the 11th of May, 2016, Hyperloop One conducted a live test of the proposed propulsion system in the Nevada Desert. A small sled was propelled, using a linear accelerator, to a speed of almost 187 km/h. This test was carried out to demonstrate the propulsion system to potential investors.

Even though SpaceX is not pursuing a commercial venture, it is involved in developing the technology by hosting competitions. There are two judging phases announced in the 2016 pod competition: a design competition that was held in January 2016 (of the “Best Overall Design Award”, Massachusetts Institute of Technology (MIT)) and an on-track competition to be held 27–29 January 2017. The competition is open to participants globally. 30 of the 115 teams that submitted their designs in January 2016 have been selected to build pod prototypes to compete on the sponsored Hyperloop test track. They will be judged on:

- Final Design and Construction
- Safety and Reliability
- Performance in Operations
- Performance in Flight

Dubai also hosted a two-day International Hyperloop competition in 2016, Hyperloop One exhibited its plans at the event for a radical undersea system connecting Abu Dhabi and Doha, which would be unique to any city in the world and could extend further to Bahrain and Saudi Arabia. One team, French outfit Team Mobius, also proposed an underwater concept that could connect Abu Dhabi to Doha in Qatar in just 22 minutes. They were

---

awarded first place based on design, safety, efficiency and sustainability with the government assessing the feasibility of a 2020 launch date.

### 2.2 MAIN COMMERCIAL VENTURES

#### 2.2.1 Hyperloop One

Even though the route between Helsinki and Stockholm is predicted to cost around $21 billion, it is also estimated by KPMG to attract an annual profit of around $903 million, resulting in a payback time of around 23 years, not including maintenance and running costs. A study is being conducted to determine the feasibility of a hybrid submerged/supported track.

The hyperloop system could be installed at the Jebel Ali port in Dubai, transporting cargo over a distance of 150 km in 12 minutes.

During later 2016, Hyperloop One revised the San Francisco to Los Angeles route cost estimate to $13-$15 billion (up from the initial $6 billion estimate). However, Michael L. Anderson, an associate professor of agricultural and resource economics at the University of California, Berkeley, considers that the cost of the entire project would be closer to $100 billion.

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2 [https://bits.blogs.nytimes.com/2013/08/15/could-the-hyperloop-really-cost-6-billion-critics-say-no/?_r=1](https://bits.blogs.nytimes.com/2013/08/15/could-the-hyperloop-really-cost-6-billion-critics-say-no/?_r=1)
2.2.2 Hyperloop Transportation Technologies

- Crowdsourced company with AECOM, UCLA, Swiss Vacuum Company (Oerlikon Leybold Vacuum) as partners
- Focused on passenger transportation only and exclusively licensed Inductrack
- Developing ‘Innovation Train’ for Germany; profits will be used to fund Hyperloop project
- India’s prime minister has confirmed joint feasibility projects to launch hyperloop
- Permits for 5 miles test track project, North California – Quay Valley
- $100 million
- Contract with government: Vienna, Austria → Bratislava, Slovakia → Budapest, Hungary.
- First Stage just in Bratislava
- Cost: $300 million
- Capacity: 10 million passengers/year

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3 http://venturebeat.com/2017/01/10/hyperloop-one-has-a-short-list-of-cities-for-its-760-mile-per-hour-trains/
The Italian high-tech holding group Angelo Investments, that leads a group of pioneering companies developing advanced technologies for the railway (MERMEC), space (SITAEL), and aviation (BLACKSHAPE) industries, announced that it had acquired a stake in TransPod Inc.\(^4\)

2.3 NON-COMMERCIAL VENTURES

2.3.1 SpaceX

- SpaceX CEO Elon Musk presented the idea in 2013
- Open source development
- Pod competition using Hypertube.
- Pod competition II - Summer 2017
  - Only judged on maximum speed
- Design competition won by MIT Hyperloop team.
  - Partners include the CEO of Magplane Technology and the VP of Magnemotion
- India has offered land for a pilot project

2.3.2 China

- Hyperloop development in China funded by the military (Maglev in Vacuum); not fully disclosed to the public
- Several research teams across China
- Not impressed with Hyperloop One demo.
- Lead researcher mentioned that there is existing technology that can accelerate pods to over 1000 km/h easily
2.4 **GOVERNMENT INTEREST**

Many governments (in India, Dubai, Russia, the People's Republic of China, USA, South Korea) have commanded feasibility studies on the Hyperloop, demonstrating their growing interest in the subject. San Francisco-Los Angeles, Helsinki-Stockholm, Dubai-Abu Dhabi, Vienna-Bratislava-Budapest, and Toronto-Montreal have been proposed as the first hyperloop routes to be deployed.

- **India** – India’s Union Transport Minister, Nitin Gadkari has offered SpaceX the westerly bypass of Pune to test a pilot project. HTT have sent a letter of intent to the Indian government.
- **Dubai** – In addition to the cargo hyperloop proposed to be installed at Jebel Ali port, the government of Dubai are working with Hyperloop One on track between Dubai and Abu Dhabi. This system is unique in that it includes ‘Hyperpods’ which can also travel on road infrastructure, offering passengers seamless door-to-door transportation.
- **US** – Hyperloop One is planning to build a track to connect San Francisco and Los Angeles and is in talks with the US government.
- **Slovakia** – HTT has signed a deal with the Government of Slovakia to connect Vienna, Bratislava and Budapest.
- **Russia** - Hyperloop One has also signed a deal with Summa Group, a Russian transportation infrastructure developer to develop a system to be integrated with the Moscow subway system, and to provide long distance travel in Russia.
- **Canada** – Government in talks with Transpod to build a hyperloop system between Toronto and Montreal.
- **Sweden and Finland** – In talks with Hyperloop One to connect Helsinki to Stockholm. Have commissioned feasibility study from KPMG.
- **People’s Republic of China (PRC)** – China’s scientists are looking to develop military applications for the experimental technology behind an ultra high-speed “vacuum” transport system.
- **South Korea** - The Korea Railroad Research Institute (KRRI) plans to develop a "hyper-tube" line connecting the capital city of Seoul with the port city of Busan (which would cover 200 miles in 30 minutes). Over the next three years, KRRI and its partners will explore the feasibility of the project. The system proposed would offer a relatively slower speed, 620 mph instead of 760 mph (traditional Hyperloop speed). Designs released by the institute show a 16-seat passenger pod that would hurtle frictionlessly through tubes under a partial vacuum.
3 HYPERLOOP TECHNOLOGIES

3.1 OVERVIEW OF SUB-SYSTEMS
The Hyperloop system, described in very high level terms, consists of a tubular infrastructure, transport pods, the pods’ levitation system, and a propulsion/braking system. The main technologies identified in the Hyperloop system and their classification are illustrated in Figure 2 (More technical details are given on each component in the Appendix).

Propulsion
The Hyperloop concept has chosen Linear Induction Motor (LIM) technology as primary source of propulsion. LIMs are rotational electric induction motors that have been unravelled. They have been used in various capacities for over 3 decades, even as part of a concept maglev train project. They are considered to be extremely apt to provide propulsion to a hyperloop pod, due to their not relying on physical contact, due to the initial levitation effect they provide, and due to their controllability. In complement to linear induction motor propulsion, the Hyperloop concept considers the use of regenerative braking. However, these two technologies have not been combined in practice yet.

Figure 2: Sub-systems of the Hyperloop
3.1.2 Levitation

As regards the levitation system itself, Maglev technology is now being preferred to the initial proposition of using air bearings. Maglev technology has indeed a longer history of tests and application to rail. However, it bears a relatively high cost for Hyperloop, due to the high power requirements of the electromagnets or super cooled electromagnets used. To save costs, the cheaper Inductrack maglev technology has been developed, which implements a Halbach array into the track and requires no external power. This technology, is however, mainly experimental.

3.1.3 Pods

The hyperloop commercial ventures are currently focusing on the development of cargo pods, and will follow up with passenger versions. Pods models vary in size depending on the journey and purpose. Renderings of a pod at the 2016 InnoTrans trade show in Berlin revealed a 10-ton vehicle 82 feet long, capable of carrying 10 tons of passengers or freight. A compressor at the front draws what little air remains in the near-vacuum of the Hyperloop tube, and pumps it to the back of the pod to minimise drag.

Figure 3: Diagram of Linear Induction Motor

Figure 4: Transpod’s capsule concept revealed at InnoTrans

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http://www.schoolphysics.co.uk/age16-19/Electricity%2520and%2520magnetism/Electromagnetism/text/Linear_induction_motor/index.html
3.1.4 Infrastructure

The hyperloop is to be run with a closed loop section under a constant partial vacuum, and small outlets for pod arrival at terminal and pressurisation.


Two options have been proposed for the Hyperloop track infrastructure. Submerged tracks would use the natural buoyancy of the air inside the tunnels to alleviate the tension in the support structures. However currently existing submerged tunnels do not have to withstand an extremely low pressure environment on the interior, which can only exacerbate the stress imposed by the pressure of the surrounding water. For this reason, non-submerged designs are the ones to have progressed beyond the concept stage. Supported tunnels offer a more practicable solution: a partially evacuated tube would be supported on pylons with bearings, which would in theory account for earthquake-induced tremors. The tube would require a multitude of expansion joints to counteract the thermal expansion experienced by the tubular steel structure.

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Figure 6: Undersea Hyperloop One track concept design

Figure 7: Supported hyperloop test track

https://d.ibtimes.co.uk/en/full/1527425/hyperloop-ones-underwater-transport-system-concept-art.jpg
### 3.2 Technology Readiness Level of Hyperloop Technologies

Respective technology readiness levels (TRL) were estimated by the Knowledge team and are presented in Table 1.

<table>
<thead>
<tr>
<th>Hyperloop components</th>
<th>Levitation systems:</th>
<th>Pods:</th>
<th>Partially evacuated tube TRL 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion and Magnetic Braking systems:</td>
<td>TRL 4</td>
<td>TRL 4</td>
<td>TRL 4</td>
</tr>
<tr>
<td>Linear Induction Motors (LIMs)</td>
<td>TRL 3.5</td>
<td>Air bearings(^9)</td>
<td>Passenger TRL 4</td>
</tr>
<tr>
<td>Regenerative Magnetic braking</td>
<td>TRL 2</td>
<td>Mag-lev TRL 6</td>
<td>Freight TRL 4</td>
</tr>
</tbody>
</table>

Hyperloop system: TRL 3-4

Table 1 - Technology readiness levels of the Hyperloop system and sub-systems

These TRLs are based on the following convention:

<table>
<thead>
<tr>
<th>TRL</th>
<th>Basic principles observed and reported</th>
<th>Technology concept and/or application formulated</th>
<th>Analytical and experimental critical function and/or characteristic proof-of-concept</th>
<th>Component/subsystem validation in laboratory environment</th>
<th>System/subsystem/component validation in a relevant environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL 1</td>
<td>Transition from scientific research to applied research. Essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.</td>
<td>Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.</td>
<td>Proof of concept validation. Active Research and Development (R&amp;D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.</td>
<td>Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.</td>
<td>Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.</td>
</tr>
</tbody>
</table>

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8 Technology Readiness Levels - method of estimating technology maturity of Critical Technology Elements (CTE) of a program during the acquisition process.

9 Air bearings - although explored initially, they have now been proven infeasible for the final Hyperloop system. They are at TRL 2-3, but omitted from the overall Hyperloop system TRL calculation.
The reasoning is as follows:

**Linear Induction Motor propulsion (TRL 5):** LIMs have been in commercial use in industrially relevant environments for over 3 decades; in low speed maglev shuttles and roller-coasters. Hence a TRL level of 6 is justified although the technology has not been demonstrated in the operational environment of the hyperloop system, i.e. a partially evacuated tube with full scale pod. Furthermore, the LIM showcased at atmospheric conditions only reached speeds of 187km/h.

**Regenerative Magnetic braking (TRL 2):** Trains and trams already utilise electro-magnetic regenerative braking systems, however most of these use tractive motors. The use of LIMs as brakes are still in the research and experimentation phases.

**Air bearing levitation for high speed transport (TRL 2):** Air bearings have not been used in any related function similar to levitating pods. The only current industrial use has been for lubrication systems, requiring vastly different design specifications than those required in the hyperloop system. Furthermore, air-bearings have been abandoned as a system of levitation by the major hyperloop developers.

**Maglev levitation (TRL 6):** Conventional maglev systems have existed and have been in commercial use for nearly 4 decades. However, these systems have been of the EDS or EMS variety. There has been no successful commercial venture using Halbach arrays to

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10 Adapted from https://esto.nasa.gov/files/TRL_definitions.pdf
levitate vehicle, although some scale model hyperloop pods with Inductrack levitation have been tested at SpaceX’s Design competition.

**Passenger/Freight pods (TRL 4):** The pods have only reached the sub-scaled model developmental phase. The sub-scaled prototypes, which carry no payload and have only some basic systems integrated, and tested for speeds much lower than 760 mph, around 58 mph. Only a singular test was conducted in an environment similar to operational. Research is still being carried out to prove the concept for passengers and freight.

**Submerged tracks (TRL 2):** No submerged floating tracks have been constructed, although many proposals have been submitted. The engineering challenges to construct a submerged, partially evacuated tunnel capable of containing pods travelling at 760 mph are so great that a preliminary feasibility study has not yet been completed.

**Supported tracks (TRL 6):** Partially evacuated tubes are used widely in industry to transfer small packages over short distances. However, there haven’t been any prototypes nearing the scale of that required for the hyperloop system; the initial proposal presented a 300km long tube. Theoretically, all the components for the supported track have been developed: vacuum pump, welded steel tubes, bearings that allow exact alignment and mitigate effect of environmental hazards such as earthquakes. The track has not been constructed and tested with these components working in unison. Even for the sub-scale models of the test tracks, only some of the above-mentioned components were incorporated. The concept has been formulated, and small scale partially evacuated track was constructed for SpaceX’s design competition.

**Hyperloop whole system (TRL: 3-4):** average of the components’ TRL.
4 REVIEW OF THE ESTIMATED COSTS AND BUSINESS CASE

Musk’s white-paper estimates the construction cost of the Hyperloop between San Francisco and Los Angeles to amount to $6 billion (or $17 million/mile) for the passenger-only version system, less than one tenth of the cost for the California High Speed Rail ($68.4 billion)\textsuperscript{11}. The Hyperloop project’s estimated cost is broken down into its component costs (excluding development costs), as shown in figure 9. According to Musk, to repay the cost of $6 billion over 20 years, the Hyperloop would have to transport 7.4 million people and price one-way trip tickets at $20.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{hyperloop_cost_table.png}
\caption{Hyperloop estimated construction cost}
\end{figure}

However, Hyperloop One quoted a much higher price during a presentation, i.e. $25 - $27 million per mile for just the technology, excluding land acquisition. For reference, the California High Speed Rail faces costs of $63-$65 million per mile and in Europe the cost of high speed rail is $43 million per mile, although those figures include land acquisition costs (but exclude rolling stock). For a Hyperloop track almost entirely underwater between Helsinki and Stockholm, Hyperloop One estimates a cost of $64 million per mile including vehicles\textsuperscript{12}. A thorough cost analysis by the Ivey Business review demonstrates that the San Francisco-Los Angeles Hyperloop will likely cost around $10 billion rather than $6 billion\textsuperscript{13}. These elements indicate that the initial costs presented by Elon Musk in 2013 are likely to have been underestimated by a factor of 2 to 5, if not, as certain critics or documents claim, by a factor of 10-15\textsuperscript{14}.

\textsuperscript{11} Hyperloop Alpha. Page 8.
\textsuperscript{12} https://hyperloop-one.com/blog/FS-Links-Hyperloop-One-Baltic-Sweden-Finland-Aland-Islands
\textsuperscript{13} http://iveybusinessreview.ca/blogs/mzawalskyhba2014/2014/01/15/hyperloop-a-100-billion-boondoggle/
\textsuperscript{14} See http://its.berkeley.edu/node/9641 and http://www.forbes.com/sites/alexkonrad/2016/10/25/hyperloop-one-seeks-new-cash-amid-high-costs/#7f14e0027854
### 4.1 Review of Construction Costs

The following table compares the figures published in ‘Hyperloop Alpha’ for the hyperloop component costs (excluding development costs) for the Los Angeles to San Francisco route, to the more conservative estimates published by the Ivey Business review (low and high scenarios).

<table>
<thead>
<tr>
<th>COST (US$ MILLION)</th>
<th>MUSK</th>
<th>IVEY BUSINESS REVIEW – LOW ESTIMATE</th>
<th>IVEY BUSINESS REVIEW- HIGH ESTIMATE</th>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPSULES</td>
<td>54</td>
<td>147</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>TUBE</td>
<td>650</td>
<td>1,650</td>
<td>2,480</td>
<td>709.2 miles of Tube</td>
</tr>
<tr>
<td>PYLONS</td>
<td>2,550</td>
<td>2,049</td>
<td>2,697</td>
<td>25000 pylons</td>
</tr>
<tr>
<td>PERMITS &amp; LAND</td>
<td>1,000</td>
<td>117</td>
<td>630</td>
<td></td>
</tr>
<tr>
<td>TUNNELING</td>
<td>600</td>
<td>468</td>
<td>1,052</td>
<td>15.2 miles of tunnel</td>
</tr>
<tr>
<td>PROPULSION</td>
<td>140</td>
<td>140</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>SOLAR PANELS &amp; BATTERIES</td>
<td>210</td>
<td>290</td>
<td>530</td>
<td>Panels cover both to and fro tubes</td>
</tr>
<tr>
<td>STATION &amp; VACUUM PUMPS</td>
<td>260</td>
<td>760</td>
<td>1,010</td>
<td>2 stations at 125 each</td>
</tr>
<tr>
<td>COST MARGIN</td>
<td>536</td>
<td>300</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>6,000</td>
<td>6,093</td>
<td>9,797</td>
<td></td>
</tr>
</tbody>
</table>

The Ivey Business review seems to provide the most thorough cost analysis found in the public domain so far, and is used as primary source for the following sections on costs breakdown. Another source used is the ‘Hyperloop Commercial Feasibility Analysis’ report.
prepared by the U.S Department of Transport for the NASA Glenn Research Centre\textsuperscript{15}. Additional justifications for the costs are provided wherever possible. These have been collated from critics of the hyperloop system when founded. They seem to corroborate the cost estimates given by the Ivey business review, as well as the cost trends predicted by the U.S Department of Transport.

4.1.1 Capsule production costs
There are two main driving factors that contribute to capsule production costs:

- The number of capsules, which depends on peak passenger load
- The production cost per individual capsule

Number of capsules
The business model proposed by the Elon Musk white paper for the Los Angeles to San Francisco route is to dispatch pods every 30 seconds during the busiest hours, and at 2 minute intervals during the quietest periods. In order to meet the stated goal of transporting 14.7 million passengers annually, it has been ventured that 100 capsules should be built rather than 40 to meet peak demand. This adjustment is based on the traffic distribution statistics provided by the US Federal Highway Administration and used by Ivey Business review.

Moreover, if the Los Angeles – San Francisco transit time is not kept to 35 mins as suggested, even more pods might be required (the re-usability of pods would then be reduced). The initially proposed 40 capsule figure is based on a transit time of 35 mins, but the transit time may have to be increased, as the track might need to be longer to decrease G-forces along curves.

Capsule production cost per unit
The production cost per individual capsule can only be estimated roughly as there is still considerable design work to be done. Many Tesla and SpaceX engineers who were involved in the Hyperloop Alpha proposal provided reassurance that costs such as the interior, doors, capsule structure, assembly, propulsion, and batteries, would reflect actual costs; these items represent around 65% of overall costs. Other design sub-components of the pod such as the compressor system (20% of production cost) are based on well developed technology used in aeroplanes for example, and are less likely to be modified. Some other theoretical costs were adjusted by the Ivey Business Review, through applying a 25-50% increase (to be conservative) on the remaining 35% of capsule production cost. This adjustment gives an overall production cost of $1.5-1.6 million per 28-passenger capsule. This is comparable to a two-seater aircraft.

The ballpark capsule production cost for the San Francisco – Los Angeles Hyperloop project could therefore amount to $147 - $159 million, in contrast to the $54 million figure stated in the white paper. Any extension of the Hyperloop would also require additional capsules.

\textsuperscript{15} atl.bts.gov/lib/59000/59300/59393/DOT-VNTSC-NASA-16-01.pdf
The cost figures for pods hence seem to have been underestimated by a factor of 2 to 3, depending on the cost analysis retained.

4.1.2 Tube construction and installation cost

Hyperloop Alpha estimates a total tube construction and installation cost of $650 million for the Los Angeles – San Francisco route. The white paper gives technical specifications for the length (563km), diameter (2.23m) and thickness of pipe walls (20mm), and assumes a raw steel market price of $0.52/kg. According to the CES Materials selector\textsuperscript{16}, this price suggests that the lowest grade steel would be used. However, the material used for the SpaceX pod competition track was found to be ASTM A1018 Grade 36 (a type of hot rolled carbon steel)\textsuperscript{17}, pricing at around $0.62/kg\textsuperscript{18} in North America. Moreover, the stated cost for steel does not account for shaping the steel, welding segments together, and finishing the interior.

A more realistic construction cost for steel would be roughly $0.60/kg for raw steel according to Ivey Business review, since buying a fully formed pipeline is costlier than just purchasing the base material. However, if the estimation was based specifically on ASTM A1018 Grade 36, which might be the likely material, the cost would be further increased.

In fact, pipeline costs tend to end up ranging from $1.00-1.50/kg of formed pipeline steel. The higher end of this cost is more probable for hyperloop, as surface roughness would have to be reduced to perfect the interior of the pipe and eliminate defects\textsuperscript{19}. Basing its calculations on practices in the oil industry, the Ivey Business review calculates additional pipe installation costs for the Hyperloop to amount to $800,000/km, or $400-600 million additional costs in total for the project.

These revised cost estimates for pipe yields an expected construction and installation cost of $2.94-4.40 million/km for the steel pipe. Adding together these costs, the uplifted San Francisco – Los Angeles pipeline cost becomes $1.65-2.48 billion.

This estimate, however, does not account for an increase in the number of tubes (ref. section 4.3.4) or in the tube diameter. Indeed, it seems that the original design underestimated the diameter needed for the pipes, as explained in section ‘Tube size’ of the Appendix. Furthermore, a 3-meter diameter tube for the Alpha estimate would not be large enough for standard 10-foot-tall shipping container, which shows how outdated these costs estimates are, given that some hyperloop firms have announced that freight will be their initial focus. It can be further argued that the rail track material, expansion joints and safety hatches have not been accounted for in the white paper. This further highlights that the tube construction and installation cost was seriously underestimated.

\textsuperscript{16} A software that enables materials experts and product development teams to find, explore, and apply materials property data.

\textsuperscript{17} https://www.badgerloop.com/documents/TubeSpecs.pdf

\textsuperscript{18} http://www.meps.co.uk/N.Amer%20Price.htm

\textsuperscript{19} See the “Suspended Track” section in the Appendix
4.1.3 **Pylons construction and installation cost**

Musk’s original plans called for 25000 pylons spaced at 30m intervals with a total cost of $2.55 billion. Pylon cost may increase if more tubes are added, which might be a possibility as mentioned in section 4.3.4; more tubes would be needed to cope with maintenance and downtime while providing the same service capacity. Additionally, one critique suggested that the pylons would need more robust seismic dampers than described in the proposal, which would significantly raise costs. Others have stated that Musk wildly underestimated the construction costs, basing their criticism on the California High Speed Rail’s (CHSR) structural costs for viaducts which is higher by a factor of 10. The CHSR provides an excellent cost comparator to the Hyperloop pylon costs as it traverses the same geological regions of California.

According to the Ivey Business review, the pylons make up for the following percentage of the overall cost/km of the California High Speed Rail:

- At the high end, a reasonable mix would be subterranean support-45%, superstructure (above ground) -45%, installation-10% yielding a maximum cost of $5.0 million/km.
- At the low end, subterranean support -35%, superstructure (above ground) -35%, installation -30% yielding a minimum cost of $3.8 million/km.

An overall cost of $2,139-2,815 million can be extrapolated using these values, quite similar to Musk’s estimates. Still, Musk’s estimates are based on unclear structural simulations for seismic activities and a low estimate for dampers. For instance, Dumbarton Bridge in the San Francisco Bay Area recently had 96 bearings installed under the road deck for a seismic retrofit. The unit price of bearings, without retrofitting costs, is $90,000. If two of these bearings were on each pylon, it would add over $4 billion.

4.1.4 **Permit and Land acquisition cost**

Land costs are equally estimated to be higher than in the Hyperloop Alpha proposal. The white paper suggests that if the system is built on pylons, landlords will be prepared to sell overhead access and pylon rights for lower prices than is required for a ground level high speed rail. However, high speed rail could also be built on pylons and developers have not pursued that option, suggesting that such cost savings compared to ground level were not judged sufficient to overcome the additional complexities and costs of elevated construction for HSR. Obtaining National Environmental Policy Act (NEPA) clearance and other permits will be another significant cost, particularly for a technology to which regulating bodies are unfamiliar. Hyperloop promoters in other countries would also face similar issues.

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21  [https://www.theguardian.com/technology/2016/may/12/hyperloop-or-over-hyped-latest-demo-does-little-to-ease-doubts](https://www.theguardian.com/technology/2016/may/12/hyperloop-or-over-hyped-latest-demo-does-little-to-ease-doubts)

22  [http://www.dot.ca.gov/hq/esc/oe/project_ads_addenda/04/04-1A5224/ad1/Addn1_IH.pdf](http://www.dot.ca.gov/hq/esc/oe/project_ads_addenda/04/04-1A5224/ad1/Addn1_IH.pdf)

Based on publicly available maps, it appears that the California High Speed Rail will need to purchase roughly 260km of rural land and 25km of urban land for a similar route to that from Los Angeles to San Francisco (along the I-5 and I-508 freeways as in Musk’s proposal). Meanwhile Hyperloop will need to purchase 173km of rural land and 7km of urban land, for the same route, to account for deviations from highways to keep lateral forces below 0.5g. This doubles the required urban land purchases, and increases rural land purchases by 15% (these segments are already fairly straight); total purchases will rise to 200km of rural land and 14km of urban land. Allowing for a range of differences in rural and urban land pricing, the projected land acquisition costs for the Los Angeles – San Francisco Hyperloop could be between $1-1.2 billion.

In order to avoid urban land purchases, and the required demolition of homes, one approach which has been proposed is to build the track by tunneling through the entire urban segment. Tunneling costs would increase by an expected $168-552 million, but would decrease land purchases by $510-949 million and pylon costs by $90-118 million.

4.1.5 Tunneling costs

Tunneling costs have been estimated by Elon Musk at $600 million for the 24.5km that are required by the design for Los Angeles – San Francisco route, with an estimated cost of $31 million/km. Exact tunneling costs are very difficult to calculate as they vary widely across different projects (changes in geology requires various types of boring and drilling equipment).

This tunnelling cost/km is low relative to other rail tunnelling costs (California High Speed Rail tunneling costs range from $67-90 million / km), however, the Ivey Business review considers that tunnelling costs for the Hyperloop must be adjusted for the fact that the Hyperloop will require a smaller bore area and less concrete reinforcements (due to the smaller bore size) than a traditional rail project. Finally, increasing the number of tubes or the tube diameter, as the sizing of the tube in the proposal was found to be incorrect, would increase the tunnel cost/km.

4.1.6 Propulsion and batteries purchase costs

Linear accelerators costs amount to around $140 million, driven by three components: materials and structural components (54%), power electronics (33%), and energy storage (13%)\(^\text{15}\). The sub-components of a linear accelerator are well understood and tested. The latter are a variant of the motors used in the Tesla Model S, implying that cost overruns are unlikely. If a 25% cost uplift is used, the expected cost range becomes $140-175 million.

4.1.7 Solar panels purchase costs

Given current solar pricing, $210 million for providing 21MW ($10 million/MW) of power seem underestimated on a MW capacity basis, and would not provide enough power for the project given the stated capacity. The solar infrastructure will likely require 53MW and will carry an overall cost between $290-530 million\(^\text{21}\).

4.1.8 Stations and Vacuum pump construction costs

The listed pricing of the white paper proposal on stations is $125 million each, one in Los Angeles and one in San Francisco, for a total cost of $250 million. These costs assume that three pods are parked in the station at any given time. However, given that Musk’s original plan only called for 40% of the pods that would be required, station peak capacity will need to increase by 25%, setting a low bound on station costs of $750 million (Ivey Business Review estimate). The Hyperloop alpha report also indicated that future branch stations were a possibility.

4.1.9 Cost Margin

“Cost Margin” was a component included in Musk’s estimate, amounting to $536 million; this “cost margin” is actually lower for the passenger version. As no explanation of the cost was offered in the white paper, it is unclear what it represents, other than a safety cushion to bring the overall cost to $6 billion (and $7.5 billion for the passenger version). As Hyperloop is still in early stages and is likely to experience cost evolution, a cost range of $300-500 million contingency value was likewise given by the Ivey business review, in order to be conservative. This contingency value itself seems particularly underestimated (for instance, dampers alone could skyrocket the cost by billions).

4.2 User and Operating Costs

User cost estimates seem to vary from one company to another, but not significantly. Elon Musk’s 2013 paper estimates the ticket price of the Los Angeles to San Francisco route at $20 to cover operational costs, while a more recent estimate from HTT is $30. These prices are cheaper than in other modes of transport for similar distances, as shown in Table 4.

When adjusting for capital costs, operating expenses and the potential for construction delays or overruns, a $60-100 ticket appears to be a more likely starting estimate\(^\text{25}\). This is a significant range, 3 to 5 times higher than Musk’s own estimate. However, the final price will depend on consumer demand, and on Hyperloop’s value compared to alternate travel options (Table 4).

Assuming that Hyperloop’s largest operating cost, energy, is fully covered by a self-sufficient solar panel system (one of the key proposal of the white paper and of some commercial ventures), there are still daily operational and management costs that have not be considered such as:

1. **Traffic control**

While the operation of the system itself would be automated, some element of human supervision is required from a command centre to address unpredicted issues. Daily Hyperloop operation would include dispatching, security, and maintenance. If this work does not take place at one of the stations, the capital cost of building and running a dispatch facility would need to be added to the cost estimate.
2. Stations

Station operating costs were not mentioned in Elon Musk’s white paper. The ticketing system proposed would be an e-ticket one bypassing the need of sales agents. However, other staffing requirements would have to be considered, such as security personnel, customer service, pod maintenance/cleaning and baggage assistance. There would also be other station associated costs such as utilities for the building, restrooms, connections to other means of travel, and amenities such as coffee shops, Wi-Fi.

3. Infrastructure Maintenance

Maintenance costs were not mentioned in the Hyperloop Alpha proposal, but components will inevitably fail and need repair. The near-supersonic speed and energy accumulated within the system permit only narrow tolerances, even narrower than high speed rail. A typical inspection and maintenance service for high speed rail includes a twice weekly visual inspection of tracks and an automated track geometry inspection every month. Presumably, an inspection pod would have to be created for the Hyperloop, to inspect the interior of the tube at normal operating speed.

4.3 Other Business Case Parameters

4.3.1 Capacity

Hyperloop pods will have a seating capacity of 28 passengers (2 x14), according to the initial concept, but could also be made longer to accommodate an even greater number of passengers, while the pylons structures could support more than one tubes as shown in some models.

The proposal states that pods will be departing every 2 minutes and could also depart at 30 seconds’ interval during peak hours. This data can be extrapolated as a maximum capacity of 3360 passengers per peak hour (assuming 28 passengers).

By comparison, other high speed means of transport such as aeroplanes or HSR have a greater capacity, more in line with economically viable large scale mass transportation. To be equally viable, Hyperloop must focus on lower cost power systems (energy efficient), greater travel speeds, faster departures (including alighting and boarding), which is in line with its initial concept.
Hyperloop has the competitive advantage of being more resilient to weather conditions than other means of transport, as the pods are enclosed in a pressurised tube. The system is protected from interactions with the natural world (trees falling over rail tracks, birds sucked into jet engines, etc.). Rail grade crossing with highways would also not be required, providing safety and reliability advantages.

### 4.3.3 Energy consumption

There is a consensus that Hyperloop will be powered by harnessing solar energy. This qualifies the technology as greener by design, although maglev and HSR are equally electrically powered and could potentially tap into solar energy in the future.

In terms of energy consumption, the hyperloop system would require 1/3 of the energy of air travel on a passenger mile basis. Musk’s white paper suggests that the energy required
per seat-mile of travel could be as low as 50 megajoules per journey between San Francisco and Los Angeles, far lower than other possible travel options. The figure below is from the white paper, but no sources or calculations are offered. If powered entirely by solar power, the net emissions of the hyperloop would be practically zero.

![Energy Consumption Chart](http://www.spacex.com/sites/spacex/files/hyperloop_alpha.pdf)

Figure 11: Efficiency Comparison Between Various Transportation Modes for Travel Between San Francisco and Los Angeles. “Model S” refers to a model of the Tesla car and “Passenger + Vehicle Hyperloop” refers to a variation of the Hyperloop concept where the pods can also be driven on the road network as normal electric cars.

**Note:** The above figure is based on the original concept by Musk which used air-bearings. The energy requirements may not be considerably different after the move to a maglev levitation since a passive system is proposed.

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Table 6: Comparison of energy consumption with other modes of transport

<table>
<thead>
<tr>
<th></th>
<th>Hyperloop</th>
<th>Air</th>
<th>Maglev</th>
<th>HSR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>Electric</td>
<td>Jet Fuel</td>
<td>Electric</td>
<td>Electric</td>
</tr>
<tr>
<td><strong>Power Source</strong></td>
<td>Solar powered with backup batteries</td>
<td></td>
<td>Grid, so mix of all energy sources in region. There is no reason maglev couldn’t be solar powered as well.</td>
<td>100% renewables via purchase of offsets (CAHSR)</td>
</tr>
<tr>
<td><strong>Energy Consumption</strong> (BTUs per Passenger Mile)</td>
<td>Short route: 5-6x more fuel efficient than air Other routes: 2-3x more fuel efficient than rail⁹</td>
<td>3,230 BTU/p-m⁹</td>
<td>1,180 BTU/p-m¹⁰</td>
<td>975 BTU/p-m¹¹</td>
</tr>
<tr>
<td><strong>Emissions-Operating Phase</strong></td>
<td>Zero</td>
<td>High, but improving over time¹²</td>
<td>Depends on Electric Source</td>
<td>Depends on Electric Source</td>
</tr>
<tr>
<td><strong>Emissions-Construction Phase</strong></td>
<td>Not zero due to manufacturing of tube and vehicles</td>
<td>Additional due to manufacturing of vehicles and construction of airport facilities</td>
<td>Additional due to manufacturing of guideway and vehicles</td>
<td>Additional due to manufacturing of guideway and vehicles</td>
</tr>
</tbody>
</table>

*CAHSR : California High Speed Rail Authority

*BTU/p-m : British Thermal Unit / passenger mile where 1KwH = 3413 BTU

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4.3.4 Resilience

Normal operations will necessarily be stopped for any repairs within the tube. The partially evacuated tubes form a closed system, which could mean that repairs on the network in one direction might affect normal operations in the opposite direction, as the whole system may require the re-pressurisation of the tubes for the workers to operate.

If the repairs are external, operations may still need to be halted to prevent any external disturbance to operations and the tube’s thorough tolerances. In a presentation, Hyperloop One commented that they will use three tubes to address the issue of maintenance. This additional tube would allow normal operations to take place during major maintenance work on the tracks. In contrast, rail and maglev systems allow for switching between tracks for track maintenance. For the maintenance and repair of vehicles, all modes share the ability to take a single vehicle out of service and replace it with others. Since the hyperloop service involves many small pods, taking one out of service will have less impact on operations than taking one of a train carriage out of service for maintenance.

<table>
<thead>
<tr>
<th>Resiliency</th>
<th>Hyperloop</th>
<th>Air</th>
<th>Maglev</th>
<th>HSR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unpressurised</strong></td>
<td>Unless multiple tubes are stacked in each direction, maintenance or repair in one section of tube would require entire route to shut down. H- One presentation mentions building 3 tubes.</td>
<td>Aircraft can be replaced to keep service going during maintenance.</td>
<td>Because the train is elevated, the guideway experiences minimal wear and tear, compared to rail. Maglev can switch between rails, to allow for maintenance.</td>
<td>Multiple tracks and sidings allow system to continue operations even while maintenance is performed</td>
</tr>
</tbody>
</table>

*Table 8: Comparison of resiliencies between different modes of transport*27

4.3.5 System Interoperability

Hyperloop operates in a depressurised environment implying that it is less likely to provide interoperability with other modes of transport. The table shows how it compares with other modes of transport. This table only considers the traditional hyperloop concept proposed in the white paper since the “autonomous hyper-pods” are still undergoing a feasibility study and the technology is still at a conceptual design stage (high speed track
from the Burj Khalifa in Dubai to the Etihad Towers in Abu Dhabi. The trip is expected to last only 12 minutes according to Hyperloop One\textsuperscript{28}).

<table>
<thead>
<tr>
<th>System Interoperability</th>
<th>Hyperloop (Traditional)</th>
<th>Air</th>
<th>Maglev</th>
<th>HSR</th>
</tr>
</thead>
</table>

- Not interoperable, cannot provide local transit
- Not interoperable, cannot provide local transit
- Not interoperable, but can provide short distance and long distance trips on same track.
- HSR track and stations can also be used by conventional intercity rail and local commuter rail, and can provide short distance and long distance trips

\textit{Table 9: Comparison of system interoperability between different modes of transport}\textsuperscript{27}

Using a phone app, passengers select an autonomous “Hyper-pod” which drives them into the station, and docks inside a waiting “transporter pod” which can house up to 4 pods at a time. The transporter pod is the one that travels through the partially-evacuated tube to the destination portal where, other Hyper-pods emerge from the transporter and head off to the final stops using normal road ways. The doors only open twice during the journey, and the whole operation is planned to be as seamless as possible.

\textbf{Figure 12: Example of a journey using Hyper-pods}

\textsuperscript{28} http://interestingengineering.com/will-hyperloop-one-will-start-first-passenger-system/
Figure 13: Hyper-pod station

Figure 14: Hyper-pods leaving transporter to join the road network

Figure 15: Hyper-pod on the road driving towards the final destination
4.3.6 The specific case of Hyperloop Freight

The Hyperloop freight service has a high chance to see the light of day before the passenger hyperloop. Several companies have stated that Hyperloop for freight will be their first achievable milestone since the system requires a lower safety margin and less redundancies. It is also less risky to prove the technology with cargo than with passengers.

Moreover, such a development might be a natural extension of the current role pipelines play in moving certain types of gas and liquid fuels such as oil, natural gas, and petrol. When discussing hyperloop as a freight mode of transport, the size limit and weight limit of a cargo-pod must be considered, currently estimated to be 10 x 10 x 40 feet to accommodate a standard shipping container.

Given that NASA researchers found that the tube needs to be three to four times the size of the pod\(^2\), this suggests a very large tube circumference (or a smaller specialised shipping container) for Hyperloop freight. Besides, there has been no discussion of what the tonnage limit for the pod would be. The tonnage limit would impact what type of freight could potentially be moved by the Hyperloop.

The existing modes of air, truck, and rail, attract certain types of cargo, and the hyperloop does not offer clear advantages for the types of cargo carried by the existing air and surface modes. Hyperloop would likely not cut into the rail market share significantly. Freight rail service has a comparative advantage when moving heavy bulk cargo that is not time sensitive. With multiple high speed rail passenger lines in place all over the world, it is notable that the idea of using high speed lines for freight has not actually been pursued. This suggests that there might not be the need for a very high speed ground freight transportation system.

5 REMAINING ENGINEERING AND SAFETY CHALLENGES

There remain many unaddressed engineering and safety issues, that hinder the chances of a passenger Hyperloop system being ready for deployment in the next decade.

5.1 ENGINEERING PROBLEMS

5.1.1 Heat dissipation
The capsule will be travelling through a partially-evacuated tube with an ambient pressure 1000 times less than the atmospheric one. This may sound like a negligible amount of air is present in the tube, however this becomes extremely significant when the nose of the capsule is pushing past it at 760mph. The heat generated from the friction between the air and capsule would be enormous and could potentially damage the capsule and its machinery. This negative effect is further exacerbated by partial vacuum in the tube, since the heat will not be able to convect away from the capsule, and must dissipate via radiation, which is far less efficient.

5.1.2 Vulnerability to Environmental hazards
The pylons supporting the tracks have been built to withstand earthquakes. Musk comments that the hyperloop would be no different with the entire tube length built with the necessary flexibility to withstand the earthquake motions while maintaining the hyperloop tube alignment. It is likely that in the event of a severe earthquake, hyperloop capsules would have to be remotely commanded to actuate their mechanical emergency braking systems.

5.1.3 Thermal expansion of track
Thermal expansion has been a problem with large tubular structures for a long time. Oil pipelines use various technologies to overcome this obstacle, with one such solution being expansion loops.

![Figure 16: An example of an expansion loop used in an oil pipeline](http://www.hcn.org/issues/42.21/oil-and-water-dont-mix-with-california-agriculture/KernOil_9787_15.jpg/image)
These are required in piping system design to
- Reduce system stress
- Limit thermal displacements

The loops provide a necessary extension of piping in the perpendicular direction of fluid flow to absorb thermal expansion. Safer than expansions, they however occupy more space. Pipeline design may use a combination of the following:
- Symmetric vs Non-Symmetric loops
- 2-D or 3-D loops
- Multiple loops

Any of the above three could be used for Hyperloop in combinations optimal to the relevant design scenario. However, none of these would be practicable within the design constraints of the hyperloop system because the turning radii required for expansion loops are far smaller than what could be feasible for a hyperloop design[^31].

The whitepaper considers slip-joints as an answer to this problem, however many of the technicalities have yet to be addressed. Considering a track, constructed from steel, stretching from Los Angeles to San Francisco, and assuming standard values for thermal coefficient of steel and a temperature range of 0°C to 40°C, means that the track would need to expand by approximately 300m to accommodate the full range of temperatures.

Slip joints could be placed at the stations, but that would mean the joints and stations would need to be able to move by 300m. Another option is to space these out incrementally, e.g. every 10m, which means incorporating around 6000 vacuum seals and/or expansion joints along the track. Having so many possible failure points in the system increase the chance of system failure as a whole. One may consider having about 3 expansion joints, each accommodating 100m of expansion, but similar problems arise as compared to having slip joints at the stations.

Finally, a problem that was not mentioned in the whitepaper is buckling stresses due to the difference in temperature between the top and the underside of the steel tube. In any sunny area where Hyperloop technologies are intended to deploy (Los Angeles, Dubai etc.), the top surface of the tube will heat up and hence expand more than the underside of the tube. This could transform the circular cross-section into a mushroom-like shape. This would not only affect the structural integrity of the tube itself, but also the internal components required to maintain smooth travel of pods, and could cause contact between the pod and the tube.

[^31]: [http://www.whatispiping.com/expansion-loop-on-piping-system](http://www.whatispiping.com/expansion-loop-on-piping-system)
5.1.4 Unclear structural simulations

The structural Finite element simulations presented in the whitepaper for the San Francisco to Los Angeles route, seem to offer no discernible value (for instance, the first and second vibration mode shapes of a three pylon section of the Hyperloop track)

![First mode shape of hyperloop at 2.71Hz (magnified x1500)](image17)

*Figure 17: First mode shape of hyperloop at 2.71Hz (magnified x1500).*

![Second mode shape of hyperloop at 3.42Hz (magnified x1500). The colour coding represents deflection (movement). Blue means that the structure has deflected a little while red means that it has moved a lot.](image18)

*Figure 18: Second mode shape of hyperloop at 3.42Hz (magnified x1500). The colour coding represents deflection (movement). Blue means that the structure has deflected a little while red means that it has moved a lot.*

Firstly, the analysis covers only a three pillar segment of the track, which is bound to behave differently from the complete track, especially since it is proposed that the entire track is manufactured out of a single welded steel tube.

Secondly it would be nearly impossible to conduct a full scale finite element analysis of the whole track length of 350 miles, due to software and computational limitations.

The analyses and above graphs seem to have been included merely to satiate non expert readers that a complete structural technical feasibility has been conducted, when it does not seem to be the case.
Another main issue with the Hyperloop system is speed and scale. It is unclear how to create a prototype which verifies the safety of these technologies while testing all necessary components. This is the aim of the pod competition held by SpaceX. However, a 1-5 mile test track does not show all the problems that could occur in a full scale Hyperloop system. Full speed cannot be reached in these tracks, which poses further problems. This results in the test tracks being merely tubular versions of maglev and high-speed rail systems.

One possible solution proposed by HTT is to create a full scale commercial system for freight transport only. All system components could be tested, optimised, and data could be collected at full scale conditions, without placing human life at risk. In order to reach maximum speed and slow down, 23.61 miles are needed - 74.56 miles are needed for a smooth ride.

5.2 Safety Issues

5.2.1 Key Safety Questions

HTT have listed several questions that seem pertinent, having important safety-related implications for the Hyperloop concept.

- How will emergencies, such as rapid depressurisation or large scale leaks, capsule malfunction, or natural disasters such as earthquakes, be accommodated for by the tube construction?
- What happens in the event of capsule depressurisation?
- What happens if a capsule becomes stranded within the tube?
- Where will the emergency exits be?
- How fast can the capsule decelerate to an emergency stop without damaging the system or passengers?
- How will the capsule behave if it encounters abnormal density air while travelling at 760mph?
- Can it be designed to survive and protect the passengers?
- How fast will the capsule decelerate if this occurs?
- Can the problem of excessive drag be overcome even in such a low pressure environment?
- What is the potential of the capsule being buffeted by supersonic airflow?
- If there is a major breach of the tube, will air fill the tube at high velocity?
- Will the perturbations and additional speed caused by this put the capsule in danger?
- Will oxygen masks work in case of a major capsule breach?
- How long will the Hyperloop system continue to run if power is lost?
- Is a fire suppression system incorporated within the capsule?
- What material and method of tube construction present the ideal combination of safety, cost and overall function (eg. Steel, carbon fibre, Kevlar etc.)?
5.2.2 Onboard Passenger emergency and evacuation
With regards to emergency evacuations, Musk discusses the use of escape hatches, however these would likely create an undue and excessive influx of air into the tube. These issues have not been addressed rigorously enough in literature.

5.2.3 Capsule deceleration due to system malfunction
The proposed system would have pods departing every two minutes on average, with this reducing to 30 second intervals during peak periods, meaning up to 7-0 capsules present in the San Francisco – Los Angeles system simultaneously. The capsules would be separated by approximately 23 miles on average. However, a serious safety hazard is present if once capsule needs to stop and the brakes fail in a subsequent capsule, since these pods can traverse 23 miles in less than 2 minutes when travelling at full speed.

NASA\textsuperscript{32} performed some preliminary calculations, assuming a speed of 660 mph, maximum acceleration of 0.5g’s, a pod launch interval of 30 seconds, and instantaneous communication between pods. It was determined that a pod can accelerate to its maximum speed in 60 seconds, and that a pod would need to decelerate at 0.5g’s to avoid collision (with a 0% factor of safety). If deceleration magnitude was increased to 0.6g, it would be able to do so with a 20% factor of safety. This results in a separation distance between pods at maximum speed of approximately 8.85km, and approximately 4.5km would be needed for a pod to come to a complete stop from maximum speed at 1g deceleration, meaning the 30 second interval proposed by Musk is feasible if only considering stopping time and distance.

5.2.4 Capsule depressurisation
Passengers may be exposed to the risk of cabin depressurisation unless safety monitoring systems can re-pressurise the tube in the event of malfunction or accident. However, since the capsules operate near the surface of the Earth, emergency pressure restoration would be straightforward (opening a valve). In the event of a minor leak, it is proposed that onboard environmental control systems would maintain capsule pressure using reserve air until the destination is reached. In case of a major leak, oxygen masks would be deployed.

However, the pressure in the tube is a thousandth than that of the surface of the earth, making conditions more comparable to space than to commercial aircraft altitude. Hence, none of the emergency measures used even by military pilots are sufficiently suitable to avoid the severe hypoxia and traumas related to decompression. The maintenance of even a partial vacuum is nontrivial and expensive. If a leak occurs, the entire tube may need to be shut down.

5.2.5 Environmental hazards
The proposed route from San Francisco to Los Angeles is prone to many earthquakes and microquakes, against which the pylons and tube infrastructure must be designed. Musk proposes that the entire tube will be built with dampers at the pylons to both

accommodate tremors and small thermal expansions. However, such dampers currently do not seem feasible.

Another concern is the wind stress on the track infrastructure. Any structure elevated 100 feet off the ground is under a lot of wind pressure, in unpredictable and multiple directions. The track essentially acts as a sail since it is a large structure stretching hundreds of miles. This is a similar problem to airflow modelling over a cylinder, yet such modelling was not undertaken.

5.3 Accident Severity
It is impossible to manufacture a completely perfect and failsafe system, due to a variety of factors. Steel and concrete beams have weak points, control software may have bugs, contractors may not meet the final specification or designers may make errors. Considering the kinetic energy of single hyperloop pod travelling at maximum velocity, the energy dissipated in a crash if all safety systems were to fail would be enormous. Assuming a pod mass of 3100kg-6200kg containing 28-100 adults weighing 80kg each, the total mass would be 5340kg-14,200kg; travelling at 760mph, the total energy in the system would be around 309-821 million Joules.

To put this in perspective, this would be the same amount of energy released when 75kg-200kg of TNT is detonated. This considerably diminishes the credibility of development plans that have imagined the Hyperloop travelling along highways and through residential areas.
The Hyperloop has been presented as a “fifth mode of transport”, next to road, air, rail, and water. Elon Musk’s past successes with Tesla and SpaceX lend credibility to the Hyperloop business model. Many governments have commanded feasibility studies, demonstrating their growing interest in the subject.

The Hyperloop was initially announced to cost one-tenth of the California High Speed Rail, and to enable even faster journeys. The main value proposition of Hyperloop is indeed to offer high speed transport at a cheaper cost than high speed rail and commercial airlines, due to lower investment costs (lighter infrastructure, less land usage and civil engineering work) and lower operational costs (full automation, lower power consumption, local energy production and storage).

However, our research and analysis shows that the announced construction and operational costs are likely to have been underestimated by a factor of 2 to 3 at minimum. The initial proposal for the Los Angeles – San Francisco stated production, construction and installation total costs of $6 billion. Many commentators believe these costs to be drastically underestimated, with the entire project amounting in reality closer to $60 - 100 billion. Likewise, the proposed individual fares of $20 per ticket have also been criticized as impossible.

Costs aside, the technical aspects of the Hyperloop have also raised doubts. Speeds over 700 mph would surpass any commercial mode of transportation currently available. There is also no evidence of the hyperloop technologies having been successfully integrated on a wide scale system level.

Finally, there remain many unaddressed engineering, operational and safety issues, that hinder the chances of a passenger Hyperloop system being ready for deployment within the next decade. For instance, it is unclear how the system will deal with heat dissipation or with the thermal expansion of the tube. Furthermore, the business model of the hyperloop relies on a very close proximity of the travelling capsules, which causes many safety concerns in case of system failure. Each traveling pod has, at around 760 mph, a kinetic energy of just over 3 million joules, which is roughly equivalent to the energy of 75 to 200 kilograms of exploding TNT. With no way of dissipating that energy in the advent of an accident and complete safety system failure (in contrast to aircrafts which can glide), the hyperloop cannot pass through residential or urban areas without becoming a great safety concern.

The proposed deployment date of the first routes (2020) seems therefore over optimistic.
TECHNICAL APPENDIX: HYPERLOOP TECHNOLOGIES

HYPERLOOP TECHNOLOGIES IN DETAIL

Pods

*Initial pod concept*

The initial pod concept from ‘Hyperloop Alpha’ was depicted with a seating capacity of 28 passengers (2 x14), a diameter of 2.23 m (frontal area = 1.4 m²) and weighing around 3100 kg. The Hyperloop will operate by propelling these aerodynamically designed pods through a steel tube maintained at around 1/1000 of normal atmospheric pressure. There will be a maximum inertial acceleration of 0.5 g on cargo/passengers, about 2 or 3 times that of a commercial aircraft on take-off and landing. At those subsonic speeds, there would be no sonic boom, hence a relatively quiet ride.

In Musk's initial concept, each capsule is set to float on a 0.5–1.3 mm layer of air provided under pressure to "skis" affixed under the pod, similar to how pucks are suspended above an air hockey table, while still permitting near supersonic speeds that normal wheels cannot withstand. An electrically driven inlet fan linked to an air compressor with a pressure ratio of 20:1 would be located at the nose of the pod to continuously pump the high pressure air stream which forms during high speed travel from the front to the rear of the vehicle (≈ 60% of air is bypassed). This resolves the problem of drag building in front of the vehicle, slowing it down (drag force generated is only 320 N). Furthermore, a fraction of the air is propelled to the skis for additional pressure, augmenting that lift gain passively due to their shape.

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33 This is explained in the section - Air bearings: Initial concept of the Appendix.
34 As a comparison, it is a more efficient compressor than the one used in the Concorde’s supersonic engine, and similar to a jet-fighter engine’s compressor.
Current concept

The current concept does not focus on air levitation systems, but rather passive maglev which is a proven technology. The reasons for abandoning the air levitation technology is explained in section - Air bearings: Initial concept of the Appendix. Hyperloop One’s technology uses passive maglev for levitation and does not include the inlet fan and compressor as in the initial design. With rolling resistance eliminated through magnetic levitation and air resistance greatly reduced because of the partially vacuum environment, the pods can still glide for the bulk of the journey (with passengers experiencing around 0.3G – 0.5G) as with air bearings.

Commercial pod concept revealed by Transpod

Renderings of a pod at the 2016 InnoTrans trade show in Berlin revealed a 10-ton vehicle 82 feet long, capable of carrying 10 tons of passengers or freight. A compressor at the front draws what little air remains in the near-vacuum of the Hyperloop tube, and pumps it to the back of the pod to minimise drag, similar to Musk’s initial proposal.

Figure 20: Transpod’s capsule concept revealed at InnoTrans
Pods prototypes: Exterior design

Three different variations of exterior design of the pods for the Hyperloop are being explored. One pod design uses Magnetic levitation\textsuperscript{36}. The second design uses air bearings, which has now been proven infeasible.

![Figure 21: Pod prototype of MIT](image1)

![Figure 22: Prototype of a magnetic levitation](image2)

The third design, used by University of Colorado Denver’s Hyperlynx team, utilises high speed wheels for speed under 100 Miles Per Hour and air bearings for higher speeds. However, the experimental lab results show that it is unlikely to reach a maximum speed of 760 mph required for the Hyperloop with the air bearings technology. This has confirmed that air bearings might not be suited for high speeds.

![Figure 23: Hyperlynx pod’s velocity profile](image3)

\textsuperscript{36} This design was used by the winner of the “Best Overall Design Award”, Massachusetts Institute of Technology (MIT).
Example: Team Hyperlynx’s pod prototype design (sub-scaled model) breakdown

**TOP LEVEL DESIGN**

The Hyperlynx Pod will be an aluminum framed, rail-guided wheeled vehicle. An ultralight foam shell shapes the ten-foot-long, two-foot max profile, three-hundred pound pod.

A 12VDC battery powers networked sensors and actuators, hydraulic disk brakes, and real-time control systems. A modular payload is featured accommodating multiple passenger/cargo configurations.

**MATERIALS**

**COMPUTING/NAVIGATION**

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**DIMENSIONS / MASS**

- **Body**: 105#
- **Pod Mass by Subsystem**: 25#
- **Stability**: 25#
- **Braking**: 100#
- **Total Mass**: 300 lbs

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Designs of the other participating teams are available on this webpage.
**Pods prototypes: Interior design**

The interior design of the pods varies from team to team. Some of the teams have solely built pods designed for cargo transport. Other teams are working on pods to transport passengers, while some designs would also allow adjustments to be made to the pod to allow both (modular payload similar to the Hyperlynx design above).

The MIT team’s initial design, for instance, did not have room for a passenger or cargo and solely relied on the engineering of the pod. New York University’s team has created a vehicle that only allows cargo transportation. The University of Colorado Denver team incorporated a removable capsule that allows it to be exchanged for a cargo hold or passenger space which is in line with the design proposed by Hyperloop One for the Hyperloop system in Dubai.

The Hyperloop One pod design for the Dubai project was named ‘Hyper-pods’, where the pods have low-drive wheel systems, that is, the pods are autonomous vehicles that can be outfitted for different purposes such as road transportation (autonomous car). Hyper-pods would come in different sizes and would seat from 6 to 100 people. Companies could have their own custom meeting pods, so could families (similar to long-distance minivans). There could even be a critical-care pod to transport patients to the hospital. The modular payload design means that the hyper-pods would be fitted within a transporter as shown in figure 25. This is explained further in section 4.3.5 of the report.

![Figure 25: Conceptual design of Hyper-pods](image-url)
Potential pod design using current best features of current pod prototypes

From the various concepts proposed and the prototypes presented by some teams, the final pod will potentially have these characteristics:

- A carbon fibre outer shell with mechanisms and structures fabricated from aerospace alloys to withstand high stresses.

- Achieving at least a 15mm levitation gap using a passive magnetic levitation system unless there is a breakthrough pertaining to air bearings.

- A lift-to-drag ratio of 14, a value similar to a Boeing 747 aircraft at similar speeds and a comparatively better lift-to-drag ratio than the Concorde which is a supersonic aircraft. There could also be a compressor in front that pumps air to the back of the pod to reduce the effect of drag.

- Stabilisation and braking using Halbach array magnets configured to generate high-drag forces when closer to the centre beam of the track. Mechanically fail-safe braking system will be implemented, meaning if the actuators or computers fail, the system will brake automatically. The system will utilize non-contact braking using an array of 400+ magnets (400 is for the pod prototype) and will be able to decelerate the pod from 2.4G, the maximum permitted acceleration under SpaceX rules.

- Lateral control using passive magnets and mechanical damping to keep the pod centred on the rail.

- Lift suspensions to reduce system vibrations and allow the pod to overcome track variations and take turnouts.
- Low speed drive system using high speed wheels which will be engaged during boarding/alighting at stations. In addition, the high speed wheels will be used for take-off and landing, that is, moving to and from magnetic levitation.

- The cabins will be windowless, with virtual/augmented reality displays.

- The pods will be autonomous with autonomous flight and drive control systems. There will be an array of redundant sensors and batteries to ensure the pod performs safely during travel.

**Infrastructure**

*Partially Evacuated Tube*

The partially vacuumed tube design has not undergone any major design changes since Musk’s 2013 white paper. The tube is specifically sized for optimal air flow around the capsule, improving performance and energy consumption at high travel speed. The expected pressure inside the tube is expected to be maintained at around 0.015 psi (0.75 Torr, 100 Pa, or around 1/1000th normal atmospheric pressure), through the use of external industrial vacuum pumps. The pumps have an optimal efficiency at this given pressure, which implies that a further reduction in pressure would be offset by increased pumping speed, greater complexity and energy requirements. This is shown in figure 27 below. Moreover, the size of the tube which is discussed in the next section, has also a significant impact on the peak power requirements to pump the tubes down in a reasonable time, and the steady state power requirements to maintain the high vacuum in the tube.

![Figure 27: Vacuum pump speed for functional pressure range](38)

The low pressure environment offers less air resistance, hence the pod is expected to experience lower frictional forces which ultimately lowers the overall drag.

Tube size

Simulations conducted by Ansys Corporation in 2013, and by NASA in 2015, showed that the tube diameter had to be substantially wider than initially proposed by the original Musk design (NASA researchers found that the diameter must be roughly twice as big as the original specification\(^ {\text{39}}\), i.e. 2 x 2.23 m = 4.46 m). This is due to the Kantrowitz limit. When a pod is travelling at a high speed in an enclosed tube containing air, there is a minimum tube to pod ratio that prevents the flow of air from choking. If the tube walls and the pod are very close to each other, the pod will behave like the plunger seal of a syringe, forced to push the entire column of air in the system. This will require a tremendous amount of energy and might cause structural failure along the tube.

It is worth noting that the new dimensions proposed by NASA assumes that the pod possesses a compressor to allow by-pass air through. If the compressor is absent as in a few designs, the tube diameter should be greater than 4.46 m.

* Figure 29 shows the rise in achievable pod Mach number (or speed) based on increasing tube diameter. This increase is dependent on the amount of space taken up by the pod outer structure, which is a ratio of dimensions shown in Fig. 28 as a non-dimensional “blockage factor” equal to \( \frac{A_{\text{diffused}}}{A_{\text{pod}}} \). The higher the factor, the lower the blockage from the pod (hollower).

**Track layout**

From the information gathered from the ‘Hyperloop Alpha’ project, a typical track layout for the Hyperloop system is as shown in fig. 30. The pods, represented by red squares, travel in proximity to each other on a rail track housed within the partially vacuumed tube. They would depart from the stations only within 2 minutes’ interval. Magnetic linear accelerators are placed at regular intervals (approximately every 100 km apart depending on the journey) around the track to propel the vehicles and passive magnetic linear decelerators are placed at strategic points to stop the pods in case of power failure.

The stations would be around 300-500 km apart, according to an interview conducted by RSSB staff at the InnoTrans Trade fair. Shorter distances are possible, but would not be cost effective. Short distances are only expected for freight. Turbines (shown in the green regions) would be used to maintain the air flow in the semi evacuated tube, acting as a wind tunnel to provide more lift to the pods. At the stops, the tubes (shown as blue sections) will be pressurised for passengers to alight and board. There are also external pumps (not shown in the diagram) that are used to maintain the partial vacuum.

![Hyperloop Track Layout Diagram](image-url)

*Figure 30: Hyperloop track layout*
Suspended track

As proposed in ‘Hyperloop Alpha’, the tube will be supported by pylons to reduce land usage. They also vertically constrain the tube, but allow longitudinal slip for thermal expansion as well as dampen lateral slip to reduce the risk posed by environmental hazards (e.g. earthquakes). In addition, the pylon to tube connection nominal position will be adjustable vertically and sideways to guarantee proper alignment despite possible ground settling. These minimally constrained pylons to tube joints will permit a smoother and more comfortable ride. Musk stated that specially made slip joints at stations will accommodate any tube length variance due to thermal expansion, but this mechanism poses some issues (see section 5.1.3 of the report). The white paper states that it is an ideal location for the thermal expansion joints as the speed is much lower nearby the stations, hence allowing the tube to be smooth and welded along the high-speed gliding middle section. The tube interior and track would also need to be extremely smooth with as low a surface roughness as possible. This is for two main reasons:

1) Supersonic air over rough surfaces could cause unpredictable turbulences and other flow artefacts which could be dangerous when interacting with pods.
2) Rough track surfaces could cause dangerous oscillations when the pod travels over it at high speed.

Submerged track

The submerged track is a fairly new concept that has been proposed by Hyperloop One. It hopes to move the shipping ports away from existing locations and have ships dock at something similar to a “giant oil platform” where they will unload their cargo. This would then be transported via underwater Hyperloop tunnels to the shore. According to Hyperloop One board member and X-Prize Foundation CEO Peter Diamandis, the company has been talking to port authorities around the world about the idea, which is currently undergoing a feasibility study.
With the price of a underwater Hyperloop system reportedly costing just 10% of a traditional rail network, Dubai is willing to invest a large capital in developing the technology. The chosen concept that the government of Dubai is exploring, is the one by French outfit Team Mobius, winner of Dubai’s two-day International Hyperloop competition in 2016. It could connect Abu Dhabi to Doha in Qatar in just 22 minutes.

Since these tunnels are designed to hover off the bottom using buoyancy, they are largely unaffected by undulations and obstacles on the sea floor. Additionally, as they are anchored at least 20 meters down using cables, they avoid the highly turbulent surface layer of the sea. Still, such a tunnel would have to deal with waves and currents, changes in water density and local variations in buoyancy, as well as the possibility of a collision with ships, large animals and submarines. Corrosion is also an issue that has not been addressed amongst many other potential issues. The likelihood of seeing an underwater hyperloop track by 2020, as proposed by Dubai’s government, seems unrealistic given the technology readiness level is estimated to be around 1.

**Levitation systems**

**Air bearings: Initial concept**
The whitepaper published by Elon Musk in 2013 states that suspending the capsule within the tube using conventional wheel and axle systems becomes impractical at high speed due to frictional losses and dynamic instability. The proposed solution is an air bearing suspension system. Some air would be siphoned from the compressor at the front of the pod (to reduce the increasing air pressure at the front as the pod travels through the track), and pushed out of metal skis.

Upon further examination and study, key stakeholders concluded that air bearings may not be a feasible solution. Many projects have researched and attempted to create working models using this methodology, with the majority being abandoned. The few projects that technically succeed, may have failed economically due to the high requirement of power to the compressor.

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40 https://hyperloop-one.com/blog/run-silent-run-deep-case-subsea-hyperloop
After the invention of the hovercraft, many designs were not continued, due to the high-power requirements of the lift fan. This is problem is exacerbated in the hyperloop system; due to the low ambient pressure, 20-30 times as much power is required to lift the pod, compared to that at atmospheric conditions. Modern air bearings are generally used in closed systems where friction needs to be reduced, such as between a housing and a rotating shaft. In these cases, the bearings work extremely well. However, they rely on mirror-finish surfaces measured in microns (1/1000mm). These small tolerances enable the air to become a viscous layer, which is needed for the bearings to function.

These tolerances may be impracticable to apply to a hyperloop vacuum tube, where large structures will be subject to significant thermal and load distortion (with precision having to be measured in mm and not microns). Even if perfect manufacture were possible, the viscous drag which the air film is subjected to, at 760mph, would cause a high rate of shear, hindering its function. There is also no precedent for running air-bearings in a near vacuum and at high speed.

The most successful example of air skis being used to propel a vehicle was perhaps the French Aérotrain. It achieved a speed of 130 km/h in 1974 by using a large gas turbine to power 9 air compressors for lift, and 2 further turbines for thrust. However, the project was scrapped in favour of what would become TGV high-speed rail.
**Mag-Lev: Revised concept**

It is unclear which MagLev system most developers are planning to use for Hyperloop. An overview of the three main maglev systems currently in use is presented below\(^{43}\).

**Electromagnetic suspension (EMS)**

Electromagnetic suspension (EMS) uses an attractive force to levitate the train carriage. A levitation magnet on the train is attracted to the conductors on the underside of the guideway, overcoming the gravitational force, levitating the train on the track up to 1cm.

To prevent contract between the sides of the track and the train (which causes friction and damages the train), guidance magnets are placed on the sides of the train’s undercarriage. These magnets also guide the train to follow the direction of the guideway track.

![Diagram of Electromagnetic suspension (EMS)](image)

*Figure 34: Diagram of Electromagnetic suspension (EMS)*

EMS is regulated, meaning it is always powered. This means the train levitates at all times, even at low speed. Furthermore, the intensity of the magnetic field strength inside the passenger compartment is comparable to the earth’s magnetic field, hence it is safe for passengers with pacemakers or people carrying credit cards or hard disks.

An EMS maglev system needs to be constantly powered, hence the train could crash into the track in-case of a power-failure. Due to this, all EMS trains are equipped with an emergency battery power supply. An EMS maglev system is used in the Transrapid train in Germany\(^{44}\).

**Electrodynamic suspension (EDS)**

An Electrodynamic suspension (EDS) train, developed in Japan, uses magnets of identical polarity to create a repulsive force between the levitation magnet on the train and the guideway magnet. No guidance magnets are needed since the magnets on the guideway are placed around the levitation magnets on the train, as can be seen from figure 35.

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\(^{43}\) [http://science.howstuffworks.com/transportEngines-equipment/maglev-train1.htm](http://science.howstuffworks.com/transportEngines-equipment/maglev-train1.htm)

\(^{44}\) [https://emt18.blogspot.co.uk/2008/10/maglev-suspension-systems.html](https://emt18.blogspot.co.uk/2008/10/maglev-suspension-systems.html)
The main difference between EDS and EMS systems is that EDS systems use super-cooled, super-conducting electromagnets. Super-conducting electromagnets produce far stronger magnetic fields than traditional electromagnets, and can be cheaper to operate since no energy is dissipated as heat in the windings.

Super-conducting electromagnets can also conduct electricity even after the power supply has been shut off, e.g. a power failure, contrary to the EMS system where levitation occurs only when the system is powered. Super-cooling the coils saves energy, however the cryogenic system used to cool the can be very expensive.

EDS systems only levitate the train after a certain lift-off speed (of around 62 mph), before which the trains must roll on rubber tires. Past this speed, the train will levitate and the rubber tires will not contact the guideway. Albeit seeming like a drawback, this is actually an advantage if a power failure caused a shutdown of the system, since the train would merely descend and roll on the tyres. When levitating however, an EDS train can hover nearly 10cm above the guideway.

One drawback of the EDS system is that it induces a high intensity magnetic field, meaning the passenger section of the train will need to be shielded, otherwise the field poses a danger for passengers with pacemakers and can damage credit cards and/or hard drives. This shielding incurs additional weight and/or cost.

45 https://emt18.blogspot.co.uk/2008/10/maglev-suspension-systems.html
**Inductrack** (Passive Maglev)

The Inductrack system is a development of the EDS system which uses permanent, room-temperature magnets to produce the necessary magnetic fields instead of using powered electromagnets or super-cooled super-conducting electromagnets.

![Diagram of the Inductrack system](http://www.magnovate.com/uploads/files/images/general_images/levitation%20tech.png)

It is difficult to find permanent magnets able to create enough levitating force. The Inductrack system solves this problem by arranging the magnets in a certain fashion called a Halbach array, affixed to the train. This array concentrates the magnetic field intensity below the array, and cancels out above it. They are also made from a neodymium-iron-boron alloy, which generates a stronger magnetic field.

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The track consists of an array of electrically-shorted circuits containing insulated wire, with these circuits aligned like rungs in a ladder. As the train moves forward, the magnetic field repels the magnets, causing the train to levitate.

There are two Inductrack designs, Inductrack I and Inductrack II. The former is designed for high speeds, while the latter is for low speeds. Trains using Inductrack technology levitate nearly an inch above the track as long as the train is moving more than a few miles an hour. The main advantages of the Inductrack system are that it requires no power to run, and is inherently failsafe. In case of a power failure, the train would maintain its momentum, slowly coming to a halt, with the levitation force only disappearing when the train is still.47 However, all magnets in a Halbach array repel each other. One needs to overcome these repulsive forces during assembly, which may pose manufacturing problems. One must also ensure the assembly will hold together during the lifetime of its use. Finally one must consider the potential of metal junk being attracted to the Halbach array. With electromagnets, one can simply cut power and remove the debris, which is not possible with permanent magnet arrays such as the Halbach array.

Propulsion and Braking system

Linear Induction Motors

Linear electric motors are used to accelerate and decelerate the Hyperloop capsule appropriately. They are to be placed at intervals (dependant on route length and other factors). Any route will have speed restrictions at different places determined by the lateral acceleration experienced by the passengers (which becomes uncomfortable at around 0.5g). This acceleration increases with greater speed and smaller turn radii. Essentially, a lower speed restriction must be enforced when the pod is travelling through a winding part of the route, compared with when it is travelling straight. These restrictions require that the Hyperloop operators can control the speed of the capsule at various parts of the route. Linear induction motors (LIMs) are used to do this. Induction motor technology is well established. LIMs are merely rotational induction motors that have been ‘unravelled’ (see Figure 40).

A rotational induction motor has two major components. A ring of electromagnets arranged around the outside (the stator) is designed to produce a rotating magnetic field. Enclosed by the rotor, is a solid metal axle, a loop of wire, a coil and some freely rotating metal part that can conduct electricity, usually a “squirrel cage”. These make up the rotor.

47 https://emt18.blogspot.co.uk/2008/10/maglev-suspension-systems.html
The rotor and the stator are separated by a small air gap. A simplified explanation of how an induction motor (with only 4 coils) works is presented below:

1.) Two pairs of electromagnetic coils, shown in Figure 39 in red and blue, are energised alternatively by an alternating current supply (coming from the leads on the right). The two red coils are connected in series, and hence are powered

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simultaneously. Similarly, the blue coils are wired in the same manner and hence are also energised together. The alternating nature of the current ensures that the current in each coil does not switch on and off abruptly, but rises and falls according to a sine wave; when the blue coils are at the most active, the red coils are completely de-energised, and vice-versa, a phase lag of 90°.

2.) As the coils are energised, they produce a magnetic field between them. This in turn induces an electric current in the rotor.

3.) The current produces its own magnetic field which opposes the initial magnetic field, causing the rotor to turn.

4.) As the coils are alternatively energised and de-energised, the magnetic fields effectively rotates around the rotor, acting as a rotating magnetic field (RMF). The rotating magnetic field causes the rotor to spin in the same direction (due to reasons discussed in point 2) albeit at a slightly slower speed. The difference in speed is called the “slip”49.

The LiMs proposed to be used in the Hyperloop system are merely unravelled versions of standard induction motors:

![Diagram of induction motors](Figure 40 - induction motors)

The “rotor” in the LiM is mounted to the capsule, and is proposed to be a piece of aluminium. The induced current flows near the rotor surface due to the skin effect50, hence interior hollows can be made to save weight. The rotor rests between the magnetic effects

of the stators, which are attached permanently to the tubes at required locations, and extend the full length over which acceleration and/or deceleration is required.

**Braking systems**
With minor modifications to the control and power circuitry, the LIMs could be used to draw electrical energy from the moving capsule, slowing it down, instead of adding motive power, while storing the energy for later use. Such systems can be up to 85% efficient, meaning most of the energy required to drive a capsule for one journey can be supplied from the energy recovered from the previous capsule’s journey. Electromagnetic eddy current brakes would allow precise and instantaneous alteration of the braking force without any contact between the pod and the tube. Some pod competition teams are implementing a mechanically fail-safe braking system, meaning that both mechanical and magnetic brakes will engage if the actuators or computers fail. Others are also using permanent magnets arranged in a Halbach array. Braking force is increased as the array of magnets are brought closer to the track, without any contact between the two.