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Acknowledgements

This undertaking could not have been possible without the participation and assistance of many individuals whose names may not all be enumerated. Their contributions are sincerely appreciated and gratefully acknowledged.

AECOM would like to express their deep appreciation and indebtedness to the team at Continuum Industries, UK, for their expertise and endless support, to all the participating Hyperloop Technology companies for their understanding spirit and input throughout the study, to our internal AECOM global Hyperloop Technical Advisor Group for their invaluable global insight, subject matter expertise and review, and finally, Transport Canada for their direction, guidance and continued support.

We thank you all.
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Section: Executive Summary
1. Executive Summary

Hyperloop is a potential new form of high-speed transportation for the movement of passengers and freight over long distances. The key component of the Hyperloop concept is the use of low-pressure tubes to move vehicles (pods) at speeds rivalling air travel. The adaptation of a low-pressure environment within the tubes minimizes aerodynamic drag (see Figure 1), allowing vehicles (pods) to reach and maintain higher speeds than existing ground-based modes of transportation while using less energy. Like railways, Hyperloop vehicles would operate within a fixed guideway environment but without the wheels that generate significant rolling friction at high speeds. Instead, the vehicles would use magnetic levitation (MagLev) along with electromagnetic (and/or aerodynamic) propulsion to glide along a fixed guideway, similar to existing MagLev technologies.

Figure 1: Example of a Hyperloop Concept

AECOM was contracted by Transport Canada to appraise and review two principal considerations concerning the evolving Hyperloop technology:

1. Can the Hyperloop concept be transformed into a viable technology that is safe for passengers and the communities where the tubes traverse?

2. Is the Hyperloop technology cost significantly more affordable than, or at least comparable to, conventional High-Speed Rail systems or developing Maglev technologies?
In order to evaluate these questions, AECOM undertook a study comprised of four key components:

- To develop an understanding of progress to date (as of March 2020) on the Hyperloop concept, a thorough literature review of the technology and initiatives was conducted.

- To understand the various engineering concepts and designs, an independent review of the technology was conducted by AECOM, which included a series of technology readiness level assessments.

- To inform the readiness of the technology for application in Canada, a hazard and risk assessment was also conducted, with the resultant risks compared to those extant in other transportation modes and a discussion provided examining how these had been mitigated.

- Finally, to gain a more complete understanding of the technology, a high-level preliminary capital and operating cost analysis was performed, which included a comparison of Hyperloop technology as a new mode with other existing transportation modes.

During the course of the study, AECOM accessed a combination of publically available literature, consulted with internal and external Hyperloop experts, and interviewed leading Hyperloop technology developers. As the published literature on Hyperloop is limited in both quantity and independent perspective, conducting interviews with the various technology developers was important in gaining insight into technical challenges, as well as the latest design considerations.

### 1.1 Key Findings

One key conclusion, based on the evidence gathered, is that Hyperloop as a mode has not yet been fully conceptualized. Many of the questions investigated could not be answered because the technology is not sufficiently mature, has insufficient information/design options, or in some cases, an absence of initial ideas.

With so many unknown aspects remaining, it is difficult to determine if Hyperloop will become a viable mode of transportation. Based on this assessment, several technical components are in the very early stages of development and likely years away from functional realization.

Although uncertainty remains over Hyperloop’s viability based on the current level of development (as of March 2020), this appraisal recognizes that the swift evolution of the concept from 2013 to date gives cause for optimism. The rapid rate of technological development and refinement over this time period reflects how challenges considered insurmountable only a few years ago have been overcome, offering a degree of reassurance that current issues might be similarly resolved.
However, such infancy in the development of several key components, such as high-speed switching and communications, leads to the conclusion that Hyperloop, in its current state, is unlikely to be ready for real-world application in the near future. Given the length of routes being considered, the phases of environmental assessment and planning, through to design and construction of transportation infrastructure at such scale, these will likely take many years to complete. In consideration, it is highly improbable that Canada can expect to see a viable commercial route until well into the next decade and, given the number of current uncertainties, this could still be claimed to be an ambitious timeline.

The level of uncertainty over the resolution of remaining challenges and timescales for the technology directly impacts the anticipated cost of the system. The study found that, when first conceived in 2013, the per kilometre system cost was estimated at $19M and is now forecast to be closer to $56M. Such a significant rise is largely due to the increased technical complexity of the system as the concept has been refined. This revised capital cost, by comparison, places the system higher in price than high-speed rail, and in some ways more comparable to MagLev technology. The study also considered how operational costs might compare with other modes, however, given the lack of known quantities and supporting infrastructure and operations, it is highly challenging at this stage of technological development to accurately quantify the operational costs of the system.

Equally, the hazard and risk assessment performed in this study shared similar gaps as a result of the significant uncertainty surrounding various key technical elements and features of the system. Although most of the risks were readily identifiable, the probability of the event was far more difficult to define. As a result, this assessment has helped to highlight the potential importance of a collaborative approach between technology developers and global governments/agencies in developing a regulatory framework. The regulatory review also sheds light on the existence of innovative elements unique to Hyperloop, which may require specific focus from regulators in the future.

Hyperloop as a new transportation concept, shows promise, however, too many uncertainties exist for it to be considered a near-term, viable alternative to present-day high-speed rail, MagLev, or aviation. The review has considered what Hyperloop’s role could be if the technology is realized. Similarly, to the insufficient maturity of the technology, the potential application of Hyperloop is also still somewhat unclear. Originally proposed as direct competition to inter-city rail travel, the possible applications continue to evolve as cross-country, commuter and freight applications are considered.

With the anticipated cost of the infrastructure being a significant factor, it seems most likely that the cost to users will be more comparable to airfares than any local land-based transportation service. This would lead to the conclusion that, should Hyperloop be commercially realized, it will most likely start as an inter-city/metropolitan connection, where it has several distinct competitive advantages over today’s rail and aviation markets. However, with so many factors still to be determined and rising capital costs, it is feasible that Hyperloop may fall short as an economically competitive alternative.
1. Sommaire

Le système de transport par tube est une nouvelle forme potentielle de transport à grande vitesse pour le déplacement de passagers et de marchandises sur de longues distances. L’élément central du concept technologique repose sur l’utilisation de tubes à basse pression pour déplacer des véhicules (nacelles) à des vitesses qui rivalisent celles du transport aérien. La création d’un environnement à basse pression dans les tubes réduit au minimum la traînée aérodynamique (voir la figure 1), ce qui permet aux véhicules (nacelles) d’atteindre et de conserver des vitesses plus élevées que celles des modes de transport terrestre existants tout en consommant moins d’énergie. Comme pour les chemins de fer, les véhicules de transport par tube fonctionneraient dans un réseau de voies de guidage fixes, mais sans les roues, qui génèrent une quantité importante de frottement de roulement à haute vitesse. Les véhicules utiliseraient plutôt la sustentation magnétique et la propulsion électromagnétique (et/ou aérodynamique) pour glisser le long d’une voie de guidage fixe, comme on le voit dans les technologies à sustentation magnétique existantes.

Figure 1: Exemple d’un concept de système de transport par tube

Transports Canada a retenu les services d’AECOM pour évaluer et examiner deux des principales considérations relatives à la technologie de transport par tube en évolution:

1. Le concept de système de transport par tube peut-il être adapté en une technologie viable et sécuritaire pour les passagers et les collectivités qu’elle traverse?

2. Les coûts associés à la technologie de transport par tube sont-ils nettement inférieurs, ou à tout le moins comparables, à ceux des systèmes de train à grande vitesse conventionnels ou des technologies à sustentation magnétique en développement?
Afin de se pencher sur ces questions, AECOM a entrepris une étude, qui comprend quatre composantes principales:

- Afin d’acquérir une compréhension de l’avancement à ce jour (en date de mars 2020) du concept de système de transport par tube, une revue de la littérature approfondie concernant la technologie et les initiatives qui y sont liées a été effectuée;

- Afin de comprendre les divers concepts et conceptions techniques, un examen indépendant de la technologie a été mené par AECOM, lequel comprenait une série d’évaluations du niveau de maturité technologique;

- Afin d’orienter l’évaluation du niveau de maturité de la technologie pour une application au Canada, une évaluation des dangers et des risques a également été réalisée. Les risques cernés ont été comparés à ceux que l’on retrouve dans les autres modes de transport, et une discussion a eu lieu afin d’examiner comment ces risques ont été atténués.

- Finalement, afin d’acquérir une compréhension plus complète de la technologie, une analyse préliminaire de haut niveau des coûts d’immobilisations et de fonctionnement a été menée. L’analyse comprenait une comparaison de la technologie de transport par tube, en tant que nouveau mode, avec les modes de transport actuels.

Pendant l’étude, AECOM a examiné une gamme de publications accessibles au public, a consulté des experts internes et externes de la technologie de transport par tube et a interrogé des chefs de file dans la conception cette technologie. Étant donné que les publications relatives au système de transport par tube sont limitées, tant en ce qui a trait à leur quantité qu’à l’indépendance des sources, il était important de mener des entrevues avec les divers concepteurs de la technologie afin d’obtenir des renseignements sur les défis techniques et les dernières considérations relatives à la conception.

### 1.1 Principales conclusions

Une des principales conclusions, fondée sur les données recueillies, est que la technologie, en tant que mode de transport, n’est pas encore entièrement conceptualisée. Il a été impossible de répondre à bon nombre des questions examinées, car la technologie n’est pas suffisamment évolution, il n’y avait pas assez de renseignements ou d’options de conception et, dans certains cas, les idées initiales étaient manquantes.

Avec autant de variables inconnues restantes, il est difficile de déterminer si le transport par tube peut devenir un mode de déplacement viable. Selon l’évaluation, plusieurs composantes techniques en sont aux toutes premières étapes de leur élaboration, et il faudra vraisemblablement des années avant qu’elles soient fonctionnelles.

Bien qu’une incertitude plane toujours sur la viabilité du système de transport par tube dans son niveau de maturité actuel (en date de mars 2020), l’évaluation reconnaît que l’évolution rapide qu’a connue le concept depuis 2013 suscite l’optimisme.
La progression rapide de l’avancement et du perfectionnement technologiques au cours de cette période montre comment des défis considérés insurmontables il y a seulement quelques années ont été surmontés, ce qui donne une certaine assurance quant à possibilité que les problèmes actuels puissent être résolus de manière similaire.

Toutefois, le faible degré de maturité de plusieurs des composantes clés, comme la commutation à grande vitesse et la communication, mène à la conclusion qu’il est peu probable que le système de transport par tube, dans son état actuel, soit prêt à être mis en application dans le monde réel dans un futur proche. Il faudra probablement de nombreuses années pour mener à bien un tel projet compte tenu de la longueur des routes envisagées et des délais requis pour franchir les étapes d’évaluation environnementale et de planification puis la conception et la construction d’infrastructures de transport d’une aussi grande ampleur. Il est donc fort improbable qu’on puisse s’attendre à retrouver une route commerciale viable au Canada avant la fin de la prochaine décennie et, étant donné le nombre d’incertitudes actuelles, on pourrait encore affirmer qu’il s’agit là d’un échéancier ambitieux.

Le niveau d’incertitude en ce qui concerne la résolution des défis restants et les délais liés à la technologie a une incidence directe sur les coûts prévus du système. L’étude révèle qu’au tout début de sa conception, en 2013, le coût du système était estimé à 19 M$ par kilomètre, et que l’estimation avoisine maintenant les 56 M$ du kilomètre. L’importante hausse est en grande partie attribuable à la complexité technique du système, qui augmente à mesure que le concept est perfectionné. À titre de comparaison, les coûts d’immobilisations révisés font que le système est plus dispendieux qu’un train à grande vitesse et qu’il se situe, en quelques sortes, plus près des technologies à sustentation magnétique. Dans le cadre de l’étude, on a également comparé les coûts de fonctionnement à ceux d’autres modes. Toutefois, étant donné l’absence de quantités connues et d’infrastructures et d’opérations de soutien liées à un système de transport par tube, il est très difficile, à ce point dans le développement technologique, d’en quantifier avec précision les coûts de fonctionnement.

De plus, l’évaluation des dangers et des risques effectuée dans le cadre de l’étude a révélé des lacunes similaires causées par l’importante incertitude liée à des caractéristiques et des éléments techniques clés du système. Bien que la plupart des risques aient été faciles à déterminer, il était beaucoup plus difficile d’évaluer la probabilité qu’un incident se produise. Ainsi, l’évaluation a contribué à souligner l’importance pour les concepteurs de la technologie et les gouvernements et organismes mondiaux de collaborer entre eux à l’élaboration d’un cadre réglementaire. L’examen réglementaire a également mis en lumière l’existence d’innovations uniques au système de transport par tube, lesquelles pourraient nécessiter une attention particulière de la part des organismes de réglementation dans le futur.

En tant que nouveau concept de déplacement, le système de transport par tube semble prometteur. Cependant, il existe un trop grand nombre d’incertitudes pour que la technologie puisse être considérée à court terme comme une solution de rechange viable aux trains à grande vitesse, aux technologies à sustentation magnétique ou au transport aérien. Lors de l’examen, le rôle que pourrait jouer le système de transport par tube, s’il venait à voir le jour, a été étudié.
En raison de son faible niveau de maturité, les applications potentielles de la technologie restent vagues. Le système a été proposé au départ comme un compétiteur direct aux services ferroviaires interurbains, mais l’horizon de ses applications possibles continue de s’élargir alors que d’autres utilisations sont envisagées, comme des déplacements à moyenne distance, des services de navettes et le transport de marchandises.

Étant donné que les coûts prévus des infrastructures constituent un facteur important, il semble très probable que le coût pour les utilisateurs sera davantage comparable à celui du transport aérien qu’à celui des services de transport terrestre locaux. Ainsi, si le système de transport par tube venait à être commercialisé, il jouerait d’abord, selon toute vraisemblance, un rôle de liaison interurbaine ou métropolitaine, pour lequel il possède plusieurs avantages concurrentiels distincts par rapport aux marchés actuels du transport ferroviaire et aérien. Néanmoins, face à de nombreux facteurs qui restent à déterminer et à l’augmentation des coûts d’immobilisations, il est possible que le système de transport par tube ne constitue pas une solution compétitive sur le plan économique.
2. Literature Review

2.1 Background and Overview

The Hyperloop concept was first introduced in 2013 with the release of Elon Musk’s Alpha paper. The paper outlined Hyperloop, a new transportation mode that utilized low-pressure tubes to propel capsules at high speeds over significant distances. The white paper was designed to be a launching point for innovation of the concept. To promote the Hyperloop concept, SpaceX, a private aerospace company owned by Elon Musk, initiated the Hyperloop Pod Competition in 2015, focused on the development and testing of a subscale prototype of Hyperloop. As one of the most successful teams in this competition, the Hyperloop team from Massachusetts Institute of Technology (MIT) unveiled the first scaled Hyperloop prototype in May 2016 and later demonstrated the first-ever Hyperloop run in a vacuum environment in January 2017. Since the release of the Alpha paper several Hyperloop companies in North America and Europe have been formed and continue to develop their own Hyperloop technologies, with the aim of advancing it to a level suitable for commercial deployment.

As interest and support for Hyperloop increased, a number of companies began to consider possible routes and locations for application of the technology. An example of this occurred in May 2016, when the Hyperloop One Global Challenge was launched to find potentially viable locations for Hyperloop networks. The challenge saw a number of different feasibility studies submitted from locations around the world, assessing the viability of Hyperloop as a mode in various corridors. These studies built on Musk’s original premise that Hyperloop could be a viable alternative to ground-based high-speed transportation. As analysis of these routes was undertaken, many of the studies found that not only would Hyperloop compete with high-speed rail, but that theoretically, it was also positioned to challenge short-haul and, in some cases, medium-haul airline routes. Although these studies were based solely on the theoretical capabilities of Hyperloop, the findings and potential benefits of such a system have resulted in further interest and investment in this technology.

With the continued interest in and development of Hyperloop technology, governments have begun to review and consider the implications and opportunities for its deployment, including considering how such technology could be governed and what form legislation, regulation, and government involvement might take. There is a limited amount of publicly available material produced by national governments and their subsidiary agencies. The establishment of the EU Commission working group on Hyperloop regulations and the U.S. Department of Transportation’s working group exploring the application of Hyperloop are two widely known government entities currently evaluating possible directions for this new technology.

As understanding and refinement of the concept by various technology developers continues, anticipated timescales for the deployment of the first route continue to change.

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1 MIT Hyperloop Team 2017 (2017). MIT Hyperloop Final Report
Although technology developers claim that Hyperloop is only years away from real-world deployment, funding, legislation, and a complete understanding of the direct and indirect impacts are still uncertain (Figure 2 provides a summary of the research locations and studies to date). The selection of articles reviewed in this study aims to provide some clarity to the level of understanding in these areas to date and consider the accuracy of some of the forecasts made.

**Figure 2: Map of Hyperloop Companies, Testing Facilities, and Major Studies**

![Map of Hyperloop Companies, Testing Facilities, and Major Studies](image)

### 2.1.1 Alpha Paper

Hyperloop as a concept was first brought to public attention in August 2013 when Elon Musk published his Hyperloop Alpha paper\(^2\). At the time, Musk dubbed Hyperloop the “fifth mode” of transportation. He described a high-speed travel experience using low-pressure tubes, magnetic levitation, and electromagnetically propelled vehicles.

Musk was reportedly motivated to develop this new mode due to his concern regarding the proposed high-speed rail connection between Los Angeles and San Francisco, which he felt was both too expensive to build and offered little in terms of journey-time savings. Musk believed his Hyperloop concept would perform better and predicted the new technology would be safer, faster, more economical, and convenient.

He posited that Hyperloop could reduce the one-way trip from 160 minutes (2 hrs 40 min) to 35 minutes using the same proposed corridor, while at the same time its net cost of construction would save up to $55B USD compared to the high-speed rail alternative.

\(^2\) Musk, E. (2013). *Hyperloop Alpha*
In publishing the Alpha paper, Musk identified a number of important considerations he felt would establish the role of Hyperloop in the larger transportation system. These included his belief that the Hyperloop system would only be suitable for distances of no more than 1,500 km, as he suggests supersonic air travel will eventually be cheaper and faster for greater distances. Another consideration raised is the impact of the Kantrowitz Limit\(^3\) and how the flow of air around the pod needs to be of a sufficient ratio to the size of the tube to avoid impacting performance. Musk proposes supporting the movement of air around the capsule by use of a fan attached to the capsule to alleviate the pressure build-up in front of the pod.

The Alpha paper also identifies a series of economic benefits anticipated by Hyperloop, including cost-saving advantages over alternative modes, as well as the possible economic stimuli that such a connection could bring. Some of the proposed benefits of Hyperloop include smaller land requirements than conventional railway tracks, a structural design that is more resilient to earthquakes as a result of its pylon dampers design, and the possibility of energy neutrality through the use of solar power.

The paper then goes into further detail explaining the Hyperloop concept and the four main parts of the system: the capsule, tube, propulsion, and the route. The specifics of each part are described, such as the differences between “passenger” and “passenger and vehicle” (those that would carry both people and freight) capsules and tubes. The safety considerations are outlined, including passenger emergencies during trips and power outages. The paper also presents initial estimates on the cost of the passenger and vehicle systems to be between $73M and $82M per capsule.

The paper focuses on the claim that Hyperloop would be a better solution for connecting Los Angeles and San Francisco, California, than the proposed high-speed rail service. The technical section outlines the characteristics of the proposed high-speed rail (speed, cost, etc.) and acknowledges the general characteristics of other modes of transportation that might be utilized, such as air, road, and rail. This information is used as the basis for comparison with the new Hyperloop technology outlined. Throughout the paper, many of the claims and statements are unreferenced, and information on the relative performance of other modes is also sparsely supported. As Hyperloop is a new concept, it is not possible to provide references for it directly, however much of the underlying technology is not new, but this is still not referenced. While it is understood that this is the original concept paper, there was the potential to refer to previous studies on futuristic modes of transportation to further substantiate some of the paper’s claims.

It is important to note that the Hyperloop Alpha paper contributes greatly to the Hyperloop industry as it is the catalyst for the development and refinement of the technology, written with the intent that others will use it as a base concept to build upon.

Almost all of the published Hyperloop articles reference the Alpha paper, or at least noted information gleaned from it, establishing the importance of Musk’s paper in developing the Hyperloop concept. The paper was published in 2013 and stated that speeds of up to 760 mph (1,223 km/h) could be achieved.

\(^3\) Kantrowitz, A. and Donaldson, C. (1945). *Preliminary investigation of supersonic diffusers*
Although this remains a theoretical possibility, to date no developers of this technology have built a capsule that has come close to these speeds. Without proof of the concept’s capability to reach these speeds, the underlying reason and benefits for the technology in Musk’s paper remain in question.

2.2 Introduction to the Review

This section of the report summarizes a selection of published study reports, papers, and articles on Hyperloop, including technical reviews, corridor analysis, and economic assessments (Appendix B provides a review of each report). Since the publication of Musk’s Alpha paper in August 2013\(^4\), interest and investment in Hyperloop has continued to grow. In selecting the material to be included in this literature review, careful consideration was given to those reports, papers, and articles currently (March 2020) deemed most relevant to this study and to the overall development of the Hyperloop concept. Due to the limited number of publications and the potential bias of papers produced exclusively by Hyperloop technology companies, a variety of academic, private, and public sector materials have been reviewed.

This literature review examines over thirty reports, papers, and articles published since the Alpha paper in August 2013. Table 1 provides a general summary by geography, publication, and content.

Table 1: General Summary of Documents Reviewed

<table>
<thead>
<tr>
<th>Geography</th>
<th>Americas</th>
<th>Europe</th>
<th>South Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studies</td>
<td>6</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Papers</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Articles</td>
<td>6</td>
<td>4</td>
<td>2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Publications</th>
<th>Studies</th>
<th>Papers</th>
<th>Articles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Analysis</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Corridor / Logistics</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Engineering Design</td>
<td>1</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

\(^4\) Musk, E. (2013). Hyperloop Alpha
To synthesize the emerging information from the various publications and inform this study, the material was further divided and examined under the groupings: Public Agencies, Economic Analysis, Corridor/Logistics, and Engineering Design as shown below. **Table 2** provides an overview of the reviewed reports, papers, and articles against the groupings. Some of the materials reviewed covered multiple focus areas, which is reflected in the table. In these instances the document was grouped based on the main focus area discussed.

### Table 2: List of reviewed Reports, Papers, and Articles

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Publication</th>
<th>Name of Report / Paper / Article and Author(s)</th>
<th>Major Focus Area(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public Agencies</td>
</tr>
<tr>
<td>01</td>
<td>2013</td>
<td>Hyperloop Alpha - Musk, E.</td>
<td>⬤</td>
</tr>
<tr>
<td>03</td>
<td>2015</td>
<td>Article: Study on Model-based Hazard Identification for the Hyperloop System, Zhao, D., Xin, W., Hessami, A., Wang, H.</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>2016</td>
<td>Article: Shared Value Potential of Transporting Cargo via Hyperloop (2016), Werner, M., Eissing, K., Langton, S.</td>
<td></td>
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<tr>
<td>05</td>
<td>2016</td>
<td>Article: Hyperloop: No Pressure (2016), Ross, P.E</td>
<td></td>
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<tr>
<td>06</td>
<td>2016</td>
<td>Academic Paper: Comparative analysis of the Hyperloop against High-Speed Rail for commuting between Sydney, Canberra, and Melbourne, Mclean, N.</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>2016</td>
<td>Study: HyperCan – Canada East – Toronto to Montreal AECOM Hyperloop One Global Challenge (2016), Loucks, B.</td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>2017</td>
<td>Article: TransPod Ultra-High-Speed Tube Transportation: Dynamics of Vehicles and Infrastructure, Janzen, R.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2017</td>
<td>Article: Initial Order of Magnitude Analysis for Transport Hyperloop System Infrastructure (2017), TransPod</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2017</td>
<td>Article: The Hyperloop Concept compared to the economic performance of other means of transportation, Paczek, P.</td>
<td></td>
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<tr>
<td>12</td>
<td>2017</td>
<td>Academic Paper: MIT Hyperloop Final Report, MIT Hyperloop Team</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2017</td>
<td>Study: Hyperloop In the Netherlands – Main Report (2017), Arup, BCI, TNO &amp; VINU</td>
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<tr>
<td>Ref #</td>
<td>Publication</td>
<td>Name of Report / Paper / Article and Author(s)</td>
<td>Major Focus Area(s)</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td>-----------------------------------------------</td>
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</tr>
<tr>
<td>15</td>
<td>2017</td>
<td>Academic Paper: Effects of Acceleration, Deceleration, and Cornering on Occupants inside a Hyperloop Capsule/Pod at Supersonic Velocities, Vijayan, S.</td>
<td></td>
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<tr>
<td>16</td>
<td>2017</td>
<td>Article: Railways of the Future Evolution and perspectives of High-Speed Rail, MagLev and Hyperloop, Gonzalez-Gonzalez, E., and Nogues, S.</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>2018</td>
<td>Article: The potential short-term impact of a Hyperloop service between San Francisco and Los Angeles on airport competition in California (2018), Voltes-Dorta, A. Becker, E.</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>2018</td>
<td>Article: Software System in Hyperloop Pod, Nikolaev, R., Idiatuallin, R. &amp; Nikolaeva, D.</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>2018</td>
<td>Study: Multicriteria Evaluation of the High-Speed Rail, Trans rapid, MagLev and Hyperloop System, M. Janic 2018 Delft, Netherlands</td>
<td></td>
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<tr>
<td>23</td>
<td>2018</td>
<td>Article: Hyperloop for Faster Travel, Parida, R.C., Fatesingh, H.S.</td>
<td></td>
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<tr>
<td>24</td>
<td>2018</td>
<td>Study: Hyperloop: Cutting through the Hype, The Future of Transport, Roseline Walker</td>
<td></td>
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<tr>
<td>25</td>
<td>2018</td>
<td>Article: Hyperloop as an evolution of MagLev, Santangelo, A.</td>
<td></td>
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<tr>
<td>26</td>
<td>2018</td>
<td>Study: Hyperloop – Opportunity for the UK supply chain (2018), Catapult Transport System</td>
<td></td>
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<tr>
<td>30</td>
<td>2019</td>
<td>Study: Missouri Hyperloop Feasibility Study, Black &amp; Veatch</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>2019</td>
<td>Study: Hyperloop in Thailand: Preliminary study on the implementation of a TransPod Hyperloop line in Thailand, TransPod</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>2019</td>
<td>Study: An overview of the current state of hyperloop development and future recommendations as envisioned by Delft Hyperloop (2019), Van Leeuwen, J.</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>2019</td>
<td>Study: Great Lakes Hyperloop Feasibility Study - Northeast Ohio Areawide Coordinating Agency Draft</td>
<td></td>
</tr>
</tbody>
</table>
2.2.1 Summary of Findings - Public Agencies

In this section, studies conducted on behalf of and published by government bodies and agencies are examined and discussed against a number of selected categories: concept details, engineering design, policies & framework, and status. Central to both the summary and the deeper dive into studies, papers, and articles is that Hyperloop, in 2020, is still a nascent technology and many national, federal, and other government agencies continue to monitor and review the viability of the technology as it progresses through various stages of testing and development. The relatively short history of Hyperloop means few articles have been produced and published by public entities. Four main papers were reviewed as published by The National Aeronautics and Space Administration (NASA), Catapult UK, Delft University, and the Dutch government.

The following reports consider the application of Hyperloop for both freight and passenger use. As expected of an emerging technology, a considerable number of areas remain in need of further research, e.g. land use requirements, battery size and capacity, regulatory requirements and testing procedures. All of the reports recognize that further design, testing, and understanding are needed to move Hyperloop closer to a point where it could be implemented in a live environment. As noted in the 2019 Delft report, the recommendation to move towards the development of a larger test facility is a logical next step. In considering the design of this facility, it is worth noting the thought given to developing a single track capable of testing a range of different pods. Should Hyperloop proceed to a point where it can be applied in an inter-city corridor, there will likely be more than one operator; hence, more than one pod design interested in operating along the route. As such, the development of a facility that can accommodate the testing of multiple different pod designs would be beneficial in reducing licensing costs and potentially allow for greater competition in the market.

Another factor highlighted by this section is the potential restriction on Hyperloop station locations. The NASA report suggests Hyperloop stations may have to be located at the edge of urban areas (similar to many airports) as there is limited opportunity to re-purpose space within the downtown core. However, there have been suggestions that Hyperloop tubes could be installed underground (similar to some rail services) in some of these urban areas. This would have a significant impact on overall origin to destination journey times, as much of the forecast demand for this service is expected to be within or between major metropolitan areas. Such station positioning could significantly improve Hyperloop’s journey-time savings over alternative modes such as airlines and slower rail services.

Although all of the documents underline the significant gap remaining between the level of technology design and the theoretical performance maximums, this is not the only area that needs to be addressed in the short term. The Delft report highlights two regulatory-based areas that licensing bodies should be thinking about at this stage in order to avoid hampering the deployment of the technology at a later date. Considerably more research is required around safety in such a system, and licensing bodies should consider how to regulate for safety now in order to provide guidance to technology developers.
Equally as important will be ensuring the system is designed in such a way as to be compatible when crossing jurisdictional borders. The European Commission is already leading the discussion on how Europe could ensure a single regulatory system for Hyperloop and other areas should begin thinking about these challenges as well.

### 2.2.2 Summary of Findings - Economic Analysis 🖼

This section examines the studies, papers, and articles prepared and published by academics and various technology companies, institutes and/or non-public agencies comparing the performance and costs of the Hyperloop system to competing modes. When Hyperloop was first conceived, it was done so in order to create a proposedly faster and more economical alternative to high-speed rail. High-speed rail services have been, and continue to be, implemented in a number of different locations and are viewed as a fairly established rapid transportation mode. As the Hyperloop concept evolves, so does the understanding of its role within the wider transportation system. This continued development also creates questions about which existing transportation mode it will most closely compete with. There are still many unanswered questions surrounding forecast speeds, travel time, infrastructure and operating costs. These uncertainties combined with the varied pod design and capacity, are central to ongoing assessments concerning the potential costs, and how Hyperloop compares with air travel, high-speed rail services and newer systems like MagLev.

The section considered a wide range of direct and indirect economic impacts of Hyperloop. As evident in several of the reports that have looked to compare Hyperloop with various other modes, the ability to effectively contrast a still unproven technology mode with existing ones is challenging. When looking at the proposed system we are comparing it to existing proven alternatives, however, factors such as the final technical design and pod technology, which are yet to be confirmed, will ultimately determine the system’s top speeds. Therefore, the reliability of journey-time savings information stated in many of the reports cannot be deemed certain. While the concept of a capsule ‘floating’ in a low-pressure environment and being capable of forward momentum under control has been proven in test environments, most of the studies are basing their comparisons on the theoretical top speeds (circa 1200kph) which, thus far, have not been achieved. This is important to consider because if the comparison with other modes was based on the current highest achieved speed of circa 400kph then the performance results would be significantly different, as MagLev trains and aircraft would have significant speed advantages over Hyperloop.

Although none of the reports represent a formal or complete business case, several identify considerations beyond the ultimate speed of the system. Among those factors requiring further research are land-use requirements. The anticipated elevated design and relatively small pylon size required for the small, lightweight tubes are expected to translate into a small land-use footprint. However, most reports have only considered the land-use requirements for the pylons themselves. This reduces the overall anticipated cost of land purchase for the route. However, as we have seen with the rights of way for power lines, although the land underneath the lines is not necessarily needed as part of the infrastructure design, the land-use that can be supported is significantly curtailed.
The presence of powerlines considerably reduces land value and should be incorporated in the economic analysis. In a similar vein, railway corridors require a right of way in order to provide sufficient room for tracks, supporting infrastructure and maintenance and emergency access, it is also reasonable to expect that access to the Hyperloop tube will need to be provided along the entire route. Most of the reports that considered access assume the route will run in an existing corridor (such as a highway corridor). However, even if the route does follow an existing corridor, the impact of the elevated tube on neighbouring land uses and the likely widening of the right of way should be recognized.

A central assumption of a number of the reports is the capacity of the pod. The figure of 28 passengers is based on the initial capacity proposed by Musk, however, pod capacities circulated by the various Hyperloop technology companies now range from 20 to 80 with different pod designs and load capacities. If the pod capacity is larger than the 28 used in most of the analyses, this could significantly impact the cost per km for a user, assuming that the increase in pod size and pod cost are not dependent variables. If the price per km was reduced, it is possible that the ticket price might reduce to a point where it could be similar to competing modes while still offering significant journey time savings, heightening the mode’s attractiveness to users. Whatever the eventual seating capacity of the pod is, it will impact the passenger cost per km significantly. As guidance, further analyses on price sensitivity should be conducted to fully understand the possible impacts to the Hyperloop business model, especially its effects on competing modal shares.

2.2.3 Summary of Findings - Corridor / Logistics Studies

The following section considers how the introduction of Hyperloop in a specific corridor could influence both the economy and existing transportation network, and what the wider impacts might be. The reports have been prepared by a mixture of academic organizations and Hyperloop Technology companies, and a number of them compare Hyperloop with other alternative transportation modes (such as MagLev or high-speed rail) to provide a comparative analysis in a specific corridor or area.

The section reviews a number of study reports, papers and articles, seeking to compare different high-speed modes. However, it is important to recognize that in a comparison between Hyperloop and high-speed rail, the same level of confidence cannot be maintained in the costing and benefits of the two modes due to significant uncertainty over the design understanding for Hyperloop, which is untested in deployment, compared to the experience held from multiple high-speed rail projects. Since the release of the Alpha paper, most of the technology development focus has been on pod design, levitation and propulsion systems.

Research into tube design and route design impact is limited at this stage. This means various elements of the Hyperloop design such as the use of prefabricated steel tubes for installation on elevated pillars is still speculative and unproven. Compared with high-speed rail where the design challenges of implementing the technology are better understood, the accuracy of costing for Hyperloop becomes more speculative.

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5 AECOM (2019). Interviews conducted with Hyperloop Technology Companies
Uncertainty over construction costs and timescales places significant doubt over the accuracy of the claims regarding the cost of different elements of the various corridors. Differences in the construction costs (in many instances cited as the major cost of the system, with operational costs being fairly low) will significantly impact the potential ticket price and hence the relative attractiveness of the mode. Building on the promise of journey time savings and prices competitive with existing market choices, a number of corridor studies make claims about the proportion of existing mode users that would switch to Hyperloop. In reviewing these studies, there are significant differences in assumed Hyperloop market shares and modal shifts from air, train, intercity bus, and automobile modes.

A variety of methods were used to forecast ridership: many used existing transportation models, some developed their own, while others used historic ridership for similar modes in combination with a price-based model. Without access to these models, it is difficult to assess the foundations or logic behind the modal shift forecasts. However, there are several assumptions that are important in effecting modal shift. Value of time is a major influence in determining mode assignment but aspects such as comfort and number of transfers also need to be considered. In many cases where a large modal shift appears, a high value placed on time savings is a key driver in forecasting shifts to Hyperloop and the major time savings it could offer travellers. Given this assumption, it is not surprising that such high levels of modal shift are expected, and since the fares reflect the value of time saved, the projected Hyperloop revenues are noteworthy.

However, there are also a number of other factors that can affect modal choice and modal shares, ranging from user familiarity with a route and ease of access, the ability to complete a trip by a single mode (avoidance of transfer penalties), to personal comfort. The value of time also fluctuates between types of users. Business users, who place a high value on time, are likely to be already using faster modes such as air and rail. As such, significant transfer from these modes could be expected if Hyperloop offered greater time savings. However, for personal trips, users tend to be much more price sensitive. Also, comfort and ease of use also tend to be important factors in determining trip choice. Colloquially, “without looking under the hood” to examine the models, it is difficult to dismiss these mode shifts. However, some of the high numbers do raise questions over the forecasting and assumptions used.

The reports in this section also expand on the immediate benefits of a Hyperloop route and describe external benefits to land use, environment, and the economy. However, much of this is based not on fact or proven theory but rather speculation or the previous impacts of other disruptive technologies. This does not mean these benefits should be discounted, simply that a more formal and comprehensive business case or cost-benefit analysis process should be conducted in order to fully capture both benefits and negative impacts.

2.2.4 Summary of Engineering Design

The initial concept for Hyperloop, proposed by Elon Musk in 2013, set the stage for a conceptual transportation mode that would change surface transportation. However, the paper also acknowledged the design of the concept was far from the finished article and that a significant amount of work remained to be done regarding the design of the capsule, tube, and supporting systems before the system could be considered ready for implementation.
The reports and papers selected provide further information on the challenges facing the technical design of Hyperloop, comprising a mixture of material that assesses various proposed system components and details the application of these devices and advises on some of the steps required to address outstanding challenges.

The proposed concept of Hyperloop for passenger and/or freight transportation has many stages to satisfy as the engineering and design moves from initial theories/concepts to prototype testing and eventually to licensing and fully certified commercial use. Developments in high-speed rail have historically been impeded by the difficulties in managing/overcoming friction and air resistance, both of which become more pronounced when vehicles approach high speeds. Adopting the vactrain concept and employing magnetically levitated trains in an airless or partly airless tube theoretically eliminates such barriers, allowing speeds in the thousands of miles/kilometres per hour to become possible. In developing the core components that tackle the primary issue, a series of subsequent design challenges arise that need addressing. These include planning for equipment malfunction, accidents, emergency evacuation, climate change related extreme weather conditions, noise, and vibration.

The rapid development of Hyperloop technology has demonstrated an interest in the technology and a belief that the system is viable. However, despite the investment and rapid rate of development, Hyperloop technology still faces significant technical challenges. John Hansman, professor of aeronautics and astronautics at MIT, has flagged issues where a slight misalignment in the tube could create an uncomfortable and potentially difficult ride for capsules. Also, several recent assessments of various routes and corridors have identified that high-speed switching of capsules remains unproven, casting doubt on the ability to develop a network of routes.

Questions have also been raised regarding the procedure and impact of power outages when a pod is kilometres away from a city and what impact this might have on safety and system operations. Questions also remain regarding the ability to maintain a vacuum over long distances and how the security of such a tempting target for terrorists could be protected.

There are several papers and articles in Appendix B that discuss analysis surrounding aerodynamics, propulsion, and suspension. They detail computer simulations of variations in the tube area, which minimize operating energy usage and optimize tube pressure and passenger-carrying capacity. Hazard identification is investigated as a way to prioritize safety, which is highly dependent on the pod and system design, and the route, among many things. The effects of acceleration and deceleration on occupants inside a pressurized Hyperloop capsule/pod at supersonic velocities are examined using proxy references, and a literature review specific to transportation mode-related injuries is included.

Overall, the reviewed papers and articles can be summarized in two parts. Firstly, those that deal with the fundamental similarities between Hyperloop and MagLev design, and how the transfer of these technical components can be achieved. The other articles address the technical gaps that still remain between the concept and its physical application, citing a significant lack of design and testing for several key areas.
2.3 Interviews

2.3.1 Leading Hyperloop Companies

To supplement these studies and provide further context to the most recent Hyperloop developments, a series of interviews were organized with leading Hyperloop developers to learn about their technology. To facilitate collaboration, it was agreed that the technical details/configurations for each Hyperloop developer would not be disclosed due to the commercially sensitive nature of the material discussed.

Instead, this study will highlight, in general terms, the advantages and disadvantages of relevant Hyperloop technology configurations and aggregate responses from different Hyperloop developers in terms of the range of performance, lifecycle cost, and readiness. Since the 2013 release of Elon Musk’s Alpha paper and the subsequent SpaceX-led pod design competition, a number of private and public entities have been formed with the aim of establishing a commercially viable Hyperloop design by developing the tube, power supply, vacuum system and surrounding infrastructure required for the operation and testing of a pod/capsule within the tube environment.

There are currently six established Hyperloop technology companies (Hardt, Hyper Poland, Hyperloop Transport Technologies, TransPod, Virgin Hyperloop One, and Zeleros) involved in the development of pods and tube systems for the commercialization of Hyperloop. In addition to these, three further groups have recently joined the Hyperloop market and are still in the earlier stages of developing a Hyperloop design (KRRI, SwissPod and China Aerospace and Industry Corporation). Table 3 summarises the Hyperloop developers involved in this study based on information provided directly by them or previously disclosed in the public domain.

Table 3: Summary of Leading Hyperloop Companies

<table>
<thead>
<tr>
<th>Hyperloop Developer</th>
<th>HQ</th>
<th>Full-time Employees</th>
<th>Testing facilities</th>
<th>Equity Funding</th>
<th>Study Participant</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHO</td>
<td>USA</td>
<td>&lt;300</td>
<td>Completed: 500m, USA Developing: 12km, India</td>
<td>&lt;$500M</td>
<td>Yes</td>
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<tr>
<td>HTT</td>
<td>USA</td>
<td>&lt;100</td>
<td>Developing: 320m, France</td>
<td>&lt;$100M</td>
<td>In Part</td>
</tr>
<tr>
<td>TransPod</td>
<td>Canada</td>
<td>&lt;50</td>
<td>Developing: 3km*, France</td>
<td>&lt;$100M</td>
<td>Yes</td>
</tr>
<tr>
<td>Hardt</td>
<td>Netherlands</td>
<td>&lt;50</td>
<td>Completed: 30m, Netherlands Developing: 3km* Netherlands</td>
<td>&lt;$100M</td>
<td>Yes</td>
</tr>
<tr>
<td>Zeleros</td>
<td>Spain</td>
<td>&lt;50</td>
<td>Developing: 2km*, Spain</td>
<td>&lt;$10M</td>
<td>Yes</td>
</tr>
<tr>
<td>Hyper Poland</td>
<td>Poland</td>
<td>&lt;50</td>
<td>Completed: 30m*, Poland Developing: 500m*, Poland</td>
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<td>KRRI</td>
<td>South Korea</td>
<td>&lt;50</td>
<td>Developing: 7km, South Korea</td>
<td>N/A</td>
<td>Yes</td>
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<tr>
<td>SwissPod Technologies</td>
<td>Switzerland</td>
<td>&lt;10</td>
<td>Developing: 40m*, Switzerland</td>
<td>&lt;$1M</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Scaled-down vehicle and tube/track
^ The table above only listed Hyperloop Developers who participated in the data collection process
2.3.2 Interviews

The literature review has considered a number of published studies and academic papers that examine/analyze Hyperloop technology, or the application of Hyperloop in a particular location. The review has provided insight into how Hyperloop has developed from the concepts presented in the Alpha paper, as well as exploring some of the wider economic and societal impacts a real-world application could create. While this information is valuable in furthering understanding and the technical design of the Hyperloop system, many of these papers are already out of date as the technology has progressed rapidly over the past few years. In order to provide commentary on the current state of the marketplace, a series of interviews with the Hyperloop technology companies was conducted. Appendix C contains some of the responses provided and key areas discussed during these interviews. Table 3 provides information on the companies who participated.

The following is a summary of the information shared by the various Hyperloop technology companies on the understanding that the technical details/configurations remain undisclosed. Appendix D contains a summary of the technical ranges provided by technology developers.

Company Structure: Several questions searched for information about the nature of the Hyperloop technology companies. When asked how they regarded themselves, respondents identified as both developers and proponents of the new technology. During the interviews, most of the companies claimed their intentions were to license the technology to make it a commercially viable product to be sold to developers. Most of the respondents shared that, in addition to private funding, they were also receiving funding from a range of other sources, including national governments, academic institutions, other private firms with a vested interest in developing the technology, and entrepreneurs. These responses support the growing interest in the technology and the belief that Hyperloop could become a viable mode in the future. Although each of the companies is identified as having headquarters in a particular country in Table 3, most also acknowledge that they currently have operations in at least two and as many as five other countries.

Testing of Hyperloop: As testing of pods and tube configurations is currently the focus for many of the companies, questions about testing facilities were posed. Most of the companies have a single testing facility while a few have two or more. When asked about larger test facilities, most disclosed preparations to develop facilities that were at least 5 km in length, and in some cases, longer facilities were being considered. Funding for these facilities was generally either public and/or from public/private partnerships. As part of the testing process, several companies shared that their pods have yet to achieve speeds greater than 100 km/h, although a few have reached speeds between 200 and 400 km/h.

Corridor Studies: The eventual purpose of developing the technology is for implementation in existing corridors where high-speed connections could offer significant benefits. When asked about involvement in corridor studies, most of the companies identified studies they had already been involved in or that they are currently supporting. Many also disclosed they had been approached by public sector agencies interested in exploring particular corridors, and that, in some cases, they had conducted their own corridor studies but that these were not yet publicly available.
Deployment: When looking at new and emerging technologies, understanding the impact and timescales is important. Most of the technology companies interviewed believe Hyperloop technology will be ready for commercial implementation within the next five to fifteen years and that it will mostly be deployed for inter-country and interstate travel.

Questions about capacity drew a mixed response, ranging from a few thousand to 20,000 an hour. Variance in anticipated headways, from a few seconds (potentially no more than safe braking distances) to about two minutes, explains the large range.

In addition to the information summarized above, the Hyperloop technology companies were questioned about technical design and specifications. These results have been used in the Concept and Engineering Design section to further support the modelling exercises there.

2.3.3 Deployment of Hyperloop

At the time of this study (March 2020), six firms are known to be developing and testing physical pods, with several others developing testing programs (Appendix E). The development of a viable pod design capable of levitation within the tube environment is a key progression step in establishing a commercially viable product. While all six companies have designed pods to scale, at present, only two firms (based on interview responses) have achieved speeds in excess of 250 km/h in their test environments.

To date, Hyperloop technology companies have taken two main approaches to testing. A number of privately funded companies, including TransPod, Hardt, and Zeleros, have proposed, or have approval, to develop small scale test facilities (i.e. 1 to 3 km in length with a scaled down tube and vehicle) at various sites in Europe. Their key purpose is to identify design issues and potential ways to reduce the overall capital and operational costs for a full-scale Hyperloop. In the future, these facilities may be extended and enlarged for full-scale testing or commercial use. The other approach, taken by companies such as Virgin Hyperloop One, is to develop a full-scale test facility (i.e. full-scale tube and vehicle) to conduct testing of their concepts. Current test facilities used by the leading technology developers have been sufficient to prove the concept of levitation for the various pod designs and, in some cases, to prove low-level speeds (relative to the projected top speed). As indicated during conversations with several of the companies, the next step is to secure the use of, or develop their own, testing facilities where pods can be tested at higher speeds.

Based on the distance and conditions required to fully test the system at speeds approaching a commercially viable rate, a test track in the region of 15 km is required (based on similar facilities used for proving MagLev technology and calculations of acceleration and deceleration).

In addition to being a sufficient length to test higher speeds, any such facility should also incorporate a range of design features that allow for full testing of switching tubes at speeds, emergency deceleration procedures, and evacuation procedures.
Developing a test track will not only facilitate further testing and refinement of the various pod designs and tube operations, but it will also assist the planning and regulatory considerations associated with a commercial-grade Hyperloop system, providing a way for governing authorities to further understand aspects such as environmental considerations, planning requirements, and construction costs. If the technology proves commercially viable, it will be necessary for authorities to establish a planning and approval process.

In addition to design and regulatory components requiring consideration, funding for such a system may be required for the commercial realization of Hyperloop. As identified through the interview process, none of the Hyperloop technology companies currently envisage themselves building and operating a Hyperloop route. Their intention is to license it to an existing transit developer, or to partner with public or private entities to deliver the route. Discussion during the interview process revealed that a number of potential groups who might be interested or well placed to deploy Hyperloop technology commercially had already been approached; at this point, none of these firms have shown a commitment or firm interest. Most participants indicated that they want to see further progression of the conceptual technology before considering commercial deployment opportunities.

2.4 Summary of Literature Review

The review of the existing literature on Hyperloop has sought to demonstrate the progress to date in taking the original concept to the position it is in today. In seeking to provide background information to support this study, this literature review has considered a total of thirty-four reports. These have been supplemented by interviews and information from Hyperloop technology companies, helping to bridge the gap between published material and current industry thinking.

Elon Musk, with the release of the Alpha Paper, created a significant amount of interest in the potential of Hyperloop. Although he is not involved in the development, a number of firms have continued the work and refined the concept. The literature review has looked at the engineering concepts and how these have been developed. It has highlighted how some of the initial suggestions, such as elevating the structure, have remained constant throughout the refinement of the concept. However, it has also served to show that some of the conceptualised elements have undergone major changes as developers have pushed the idea towards commercialization. A prime example of this is the transition from the ‘air cushion’ concept to magnetic levitation, a proven technology already used by MagLev trains.

Accessible literature on the development of the pods and other more sensitive components is almost nonexistent, but this is to be expected given the competition among developers to commercialize the technology. Where more of the publicly available material exists is in the assessment of the application of Hyperloop in particular corridors. Most of these are published, or at least supported by the technology developers, and indicate that Hyperloop will offer vastly superior travel times, journey experience and a range of wider economic benefits compared to other modes. Certainly, these reports lead readers to believe that Hyperloop can offer many advances for ground-based travel, and that the investment will quickly pay off. These studies also point to the cost per km of Hyperloop being lower than that of other competing modes, but without a real-world application of Hyperloop yet the capital costs are mostly guesswork.
The literature helps to provide an overview of the early stages of Hyperloop development, but information supplied by the technology developers is required to understand the more recent developments. The interviews with developers revealed that most of them have viable solutions to key aspects such as levitation, propulsion and guidance. However, significant questions regarding Hyperloop have yet to be answered. Hyperloop technology companies have indicated that their intention is to license the technology but, at present, no investors have made firm commitments to the planning of a route. Equally, questions regarding the cost per km remain as many of the studies show a continued spiralling of capital costs as the technology continues to evolve.

There is very little on regulation and oversight of the industry. The formation of the European Commission’s working group and a similar USDOT working group indicate that consideration of the ways in which Hyperloop might be implemented by transport agencies has begun, however both of these groups are still in the early stages of establishing their remit and objectives. The literature review and interviews have highlighted the significant gaps in areas of cost, wider economic and environmental impacts, and legislation on Hyperloop. This report aims to provide information to support a further understanding of some of these gaps.
Section: HYPERLOOP CONCEPT AND ENGINEERING
3. Hyperloop Concept and Engineering Design

3.1 Introduction

Since the Hyperloop concept was first conceived, less than ten years ago, significant investment and testing has taken place to establish the feasibility of key principles and certain subsystems required to realize this technology. This section will review the fundamental engineering design considerations of the Hyperloop concept, to assess whether initial claims made about the performance of the technology are credible, and to establish which elements of the system need further refinement.

To date (March 2020), all Hyperloop technology developers have proceeded with designs based on the use of low-pressure tube environments maintained by vacuum pumps. The tubes provide a low friction system for the high-speed, low-energy movement of vehicles and, as the environment being used by the various developers is the same, the most substantial differences lie in the design of the various components responsible for frictionless travel, both on the pod and within the tube. These features are the major focus of the analysis, and are predominately based on propulsion, levitation, guidance, and power delivery. Table 4 provides an overview of this chapter, covering noted topics of discussion.

Table 4: Summary of Section 3 Content

<table>
<thead>
<tr>
<th>Sub section #</th>
<th>Sub-section Topics</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1, 3.2.2</td>
<td>Infrastructure</td>
<td>Provides a detailed description/analysis of common components of the tube system and associated infrastructure</td>
</tr>
<tr>
<td>3.2.3, 3.2.4</td>
<td>Propulsion and Power Delivery</td>
<td>Provides a detailed description/analysis of relevant technology options.</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Levitation and Guidance</td>
<td></td>
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<td>3.2.6</td>
<td>System Topologies</td>
<td>Provides a conceptual illustration of the arrangement of combined technology options</td>
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<td>Example System Configurations</td>
<td>Provides a detailed description/analysis of relevant system configurations</td>
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<td>3.2.8</td>
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<td>Provides a detailed description/analysis of relevant operational considerations</td>
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<td>3.2.9</td>
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<td>Provides description/analysis of possible side effects of the technology</td>
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<td>3.2.10, 3.2.12</td>
<td>Considerations</td>
<td>Summarises some of the key findings from this analysis and inputs from the questionnaire responses</td>
</tr>
</tbody>
</table>

To facilitate collaboration with each Hyperloop developer, it was agreed this report would not disclose sensitive technical details or identify the specific configurations of any particular Hyperloop technology company. Consequently, questionnaire responses are aggregated into ranges to provide anonymity and the resulting analysis will seek only to describe the key trade-offs between the different technology configurations in development.
As part of the engineering design review, several models using Python version 3.7 (refer to Appendix F), were developed to test various technology components and configurations, and reaffirm existing components and design solutions advanced by the Hyperloop technology companies. It is important to note the models are based on information provided by the companies through the questionnaire process. The parametric models were used to simulate the performance of different Hyperloop systems and estimate their costs. The models can be broadly split into four categories:

- Technology models (e.g. propulsion, levitation, power delivery)
- Trajectory models (e.g. vehicle movement)
- System models (e.g. combined technology and trajectory models that form a system for a given route)
- System of systems model (e.g. a range of different possible system models)

Further details of the modelling process can be found in Appendix F.

**Technology Readiness Levels**

The known and established NASA Technology Readiness Levels (TRL) framework and criteria were used to examine Hyperloop technology. In using this framework, it became evident during the assessment process that applying a single TRL rating to the overall system would be both challenging and not in keeping with the objectives of this feasibility study without examining each individual Hyperloop technology company’s approach and assumptions within the context of their overall system. Given this high variance and the high number of multiple and complex combinations in systems, the TRL assessment focused on those major technology elements that are potential common building blocks of a Hyperloop system. The estimated TRL reflects tangible analysis, defendable data, and reliable/credible documentation sources.

Each proceeding sub-section on the major technology elements as listed in Table 4 are discussed and assessed, followed by this study’s estimated TRL grade. Figure 3 provides an overview of the various levels and Appendix G provides further detail, definition, and context.

**Figure 3: Overview of Technology Readiness Levels**

6 [https://www.nasa.gov/directorates/heo/scan/engineering/technology/txtAccordion1.html](https://www.nasa.gov/directorates/heo/scan/engineering/technology/txtAccordion1.html)
3.2 Engineering Design Requirements and Challenges

3.2.1 Infrastructure

The primary infrastructure feature of the Hyperloop system is a continuous low-pressure tube connecting two locations that would either be installed underground, effectively creating a tunnel, or elevated above ground using pylons.

The elevated tube format, see Exhibit 1, is understood to be the preferred approach. However, in dense urban areas with no suitable corridor, the below surface format (underground solution) would provide an alternative option. The below surface format is less preferable due to the cost of boring/cut and cover construction techniques and potential existing utility conflicts. The above-ground design allows for easier access maintenance and security, a lower infrastructure footprint relative to most other transport infrastructure installed at-grade, and the potential for increased corridor capacity in congested areas. The travel speeds envisaged will limit the maximum curvature and gradient of the infrastructure alignment, which might limit the number of suitable routes in urban areas7.

A clear benefit of the pressurized tube, whether constructed underground or elevated, is that it can potentially protect the system from adverse environmental effects, such as flooding or bad weather, and removes the possibility of vegetation or wildlife impeding the path of the vehicles, notionally reducing maintenance costs and the risk of service disruption along the corridor. However, it should be noted that the tubes are expected to require regular maintenance and could be at risk of damage from extreme environmental events.

Exhibit 1: Artist Rendering of Elevated System

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7 Transpod, Initial Order Of Magnitude Analysis For Transpod Hyperloop System Infrastructure, Canada, July 2017
Tube diameter and choice of material are also important engineering design considerations. The choice of tube diameter is a complex trade-off between vehicle size, speed, power consumption, and cost, whereas the tube material used is a trade-off between stiffness (i.e. structural strength), leakage, environmental impact, and cost.

Based on public information and their questionnaire responses, we know Hyperloop developers intend to use a tube diameter of three (3) to five (5) metres and the most common material of choice referenced has been steel, followed by reinforced concrete (or a combination of the two). While both materials are recognized as preferred construction material by developers, further testing and understanding are needed to assess their application for different environments.

Developers have identified other materials such as fibreglass and certain plastic composites that could support a low-pressure environment. However, development costs and the limited availability of infrastructure capable of producing the quantities required has, to date, constrained research into these alternatives.

There remain some challenges in the construction of Hyperloop infrastructure, notably if the tube is elevated above the ground on pylons. The high speed of travel coupled with the long, continuous tube structure can result in a high dynamic amplification factor (i.e. damaging vibrations)\(^8\).

To overcome this, tube designs will either have to be much stiffer than conventional designs suggest, or the length of continuous tube sections will have to be reduced to only a few pylon spans. This, in turn, may negatively impact the low-pressure environment due to the increased number of joints and the complexity of installation.

Independent research also suggests that current code-based design regulations across the globe are insufficient for the design of such systems. However, this analysis assumes that the tube is made of steel; an alternative is precast fibre-reinforced concrete, which may offer higher stiffness at a lower cost.

Another option could be to separate the vacuum structure from the load-bearing structure by constructing the tube and guideway on top of girders (reducing the potential for stress on the tube itself), which allows the design to be optimized for load-bearing capacity without compromising the vacuum. Since structural strength is a major factor, and based on the level of vacuum desired, the low-pressure environment could be maintained using lighter materials such as thin-walled steel tubes or a synthetic membrane operated under tension to maintain rigidity, as suggested by some companies\(^9\).

This arrangement also offers an opportunity to use a combination of various materials within their optimal use range (e.g. pre- or post-tensioned reinforced concrete girders for load-bearing structures and a thin-walled steel tube for the vacuum structure).

\(^9\) Hyperloop Technologies, 'Low-Pressure Environment Structures', USA, January 2016
To date (March 2020), several short distance Hyperloop tube prototypes (based on full-scale tube and pods) have been built and tested for structural integrity, leakage rates\textsuperscript{10}, and vehicle operations at low speeds\textsuperscript{11}. However, there remain several aspects of Hyperloop infrastructure that have not yet been tested at scale, such as:

- Tube junctions with high-speed track switching;
- Passenger-friendly airlock systems;
- Emergency exits;
- Noise impacts on neighbouring land use;
- Thermal expansion over a long distance;
- Station/portal systems; and
- System performance under high-speed operation

As not all scaling issues have been fully addressed at this point, this study’s TRL of Hyperloop Infrastructure is currently estimated around \textbf{Level 4}, see \textbf{Figure 4} for further details

\textbf{Figure 4: Estimated Infrastructure TRL}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Estimated Infrastructure TRL}
\end{figure}

\subsection*{3.2.2 High-Speed Tube Switching}

One of the more unique and complex elements of the proposed Hyperloop system is the challenge of changing/switching tubes at high speeds. This is a new technology and very little is known about how it will work and exactly what the engineering challenges are. Two primary scenarios where high-speed switching is required are envisioned at this stage. Firstly, switches will be needed if Hyperloop networks are established, to allow tubes to diverge towards different destinations. Without the switches, the system would be limited to a simple point to point tube.

\textsuperscript{10} Virgin Hyperloop One, Hardt, Eurotube
\textsuperscript{11} Virgin Hyperloop One, Hardt
Secondly, with the significant volume of pods anticipated by many of the developers, it is unlikely that a single tube will be sufficient to supply a terminal location with the throughput required. Hyperloop technology developers envisage a scenario where several kilometres from a terminal, a high-speed switch location will be required to split the main tube in two, providing additional capacity for the envisaged acceleration and deceleration stages.

If the volume of travel reaches the levels some predict, it is likely a larger number of portals (entry/exit points from terminals) will be needed. This could require several phases of switches to create more tubes at the terminal, in the same way that this concept is already seen at many larger rail stations.

The concept of track-switching for MagLev technologies is not completely unproven, some of the existing systems currently employ a mechanical based switching system on their networks, but this is limited to very low speeds. Due to the complexities of the system and the tolerance of the mechanical systems, the switching occurs at significantly slower speeds than the operational maximum.

The theory of implementing high-speed switching with only electromagnetic components (i.e. without moving parts) exists but remains to be proven at scale. The expectation of several of the current Hyperloop developers is that high-speed switching technology (at more than half of the vehicle’s top speed) will be possible. However, this is still in the early stages of development.

There is currently no known scaled version of a high-speed switch and although the theory exists, there appear to be a significant number of outstanding challenges to implementing a magnetic-based switching system. This means the technology component is currently estimated at Level 2, see Figure 5 for further details.

**Figure 5: Estimated Vacuum Pump and Power Stations TRL**
3.2.3 Vacuum and Power

While the tube forms the main infrastructure element in the design of the Hyperloop system, a couple of other discrete pieces are likely to be part of all Hyperloop system designs: electrical power substations and vacuum pumping stations. The current vision for these supporting pieces of infrastructure is that they would be constructed outside the tubes at semi-regular intervals. The spacing of both systems will depend on the final tube design material and construction process. Leakage from the tube will determine the number and size of the vacuum pumping stations, which in turn, will be governed by the tube’s design.

Electrical power substations will be installed to connect various components of the Hyperloop infrastructure to the electrical grid. The Hyperloop system requires the provision of power in a controlled manner for a number of different subsystems, potentially including propulsion, power transfer systems, battery charging systems, and/or vacuum pumping stations. Each substation will be housed in a separate building (Exhibit 2), and the number and spacing of substations along the tube will vary depending on the electrical properties of the Hyperloop system.

The vacuum pumping stations will maintain the low-pressure environment inside the tube, allowing vehicles to move efficiently at high speeds. These are likely to be smaller and more numerous than the electrical power substations and may be housed in a separate building or attached to the tube exterior.

In the questionnaire responses, Hyperloop developers indicated they expect the vacuum pumps will only consume significant power during the initial pump-down (i.e. when the tube is depressurized from atmospheric pressure). Such depressurizing could be scheduled (e.g. overnight, depending on schedules) to reduce the cost and impact on the wider grid. While it seems probable that the initial pump-down would be the most energy-consuming, the number of times such an event would be required is less certain and is not known at this time. Little to no information exists regarding the amount of maintenance potentially required by the Hyperloop tube and associated infrastructure.

Given that the tube operates under a low-pressure environment and the anticipated operating arrangement for the pumps would mean they are not constantly running, it is predicted that the impact of a pump or two being down concurrently should not adversely impact operations and overall maintenance needs. It is not known at this time how long it would take to depressurize each segment as it is dependent on the number of pumps installed, their power-rating (i.e. high-cost and short pump-down time, or low cost and long pump-down time), and the length of each tube section.

At present, technology developers have not identified how they will address these questions, although it is noted that the concept of maintaining the vacuum will likely require some degree of continued effort.
Exhibit 2: Example of a Vacuum Pump

Full-scale\textsuperscript{12} vacuum pump systems have been built and tested at several Hyperloop test facilities. Where the information is available, it is known that these were installed by Leybold\textsuperscript{13}, a company specializing in vacuum pump systems.

Electrical power substations, where applicable, are likely to be similar in design to those used in present-day MagLev systems because Hyperloop substations will be powering the same types of components and are expected to require a similar or lower power supply\textsuperscript{14}. Although several designs currently proposed by technology companies suggest power could be delivered through renewable energy sources, no details have been provided and the feasibility of such an approach remains unknown.

As scaling and development issues have been addressed but stations have not necessarily been demonstrated at their final configuration, this study’s TRL of Hyperloop Vacuum Pump and Power Stations is currently estimated around \textbf{Level 6}. See \textbf{Figure 6} for further details.

\begin{itemize}
\item\textsuperscript{12} Virgin Hyperloop One, HyperloopTT, Hardt
\item\textsuperscript{13} https://www.leybold.com/uk/en/media/news/hyperloop-transport-into-the-future/
\item\textsuperscript{14} Toth D, ‘Hyperloop Power Systems’, University of Edinburgh, January 2019
\end{itemize}
3.2.4 Propulsion and Power Delivery

Arguably, the most important distinction between the different Hyperloop technologies under development is the choice and design of the propulsion system used to move the vehicles within the tube. This is because the propulsion system has a significant impact on how other key subsystems are designed and therefore impacts the overall performance and lifecycle costs of the system.

Two very different types of propulsion technology are used in Hyperloop systems: linear motors and axial compressors. Linear motors generate thrust through the interaction of magnetic fields on the infrastructure and the vehicle, while axial compressors compress air in front of the vehicle and force it out of the back at higher energy, generating thrust.

There is often confusion about how compressing air in the near vacuum of Hyperloop generates thrust. Although there is very little air in the tube, it is held in a space cross-sectionally not much larger than a Hyperloop vehicle - i.e. there is a small bypass ratio or a large blockage ratio. Hence, what little air is left can only flow in the narrow boundary between the tube and a vehicle, where it gets accelerated and consequently slows the vehicle down.

With a compressor, some of this air can be forcefully accelerated through the vehicle instead of passively flowing around it, reducing drag and generating some thrust but consuming energy. However, this effect only becomes significant when travelling at high speed, hence making compressors impractical for the initial acceleration phase\textsuperscript{15}.

\textsuperscript{15}NASA’s Open-Source Conceptual Sizing Models for the Hyperloop Passenger Pod for more information: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150000699.pdf
At low speeds and in a low-pressure environment, axial compressors are too inefficient to create adequate thrust\textsuperscript{16}. However, they can be combined with a linear motor to generate additional thrust, particularly at higher speeds when the efficiency of axial compressors increases.

Moreover, the aerodynamic drag reduction benefits of axial compressors may make them worthwhile in certain Hyperloop system configurations. Indeed, the original Hyperloop Alpha paper included compressors primarily for drag reduction and levitation purposes\textsuperscript{17}, though the latter was proven to be impractical (see Levitation and Guidance section for more details).

More recent system designs direct the full force of the compressor into propulsion, while still providing drag reduction benefits\textsuperscript{18}. Although the use of an axial compressor has been considered by several developers, its exact configuration in the pod design is considered sensitive information. The location will be important in determining the internal space arrangement for potential passengers or freight use.

**Figure 7** illustrates the simplified aerodynamics of an axial compressor. Linear motors, by comparison, are very efficient at lower speeds, but that efficiency decreases at higher speeds. From a system point of view, linear motors also contribute to infrastructure costs (as explained later in this section), whereas axial compressors do not.

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\textsuperscript{16} Coelho TMLSS, ‘Hyperloop Alpha - Conceptual study (aerodynamics)’, University of Lisbon, 2016

\textsuperscript{17} Musk E, ‘Hyperloop Alpha’, USA, August 2013

\textsuperscript{18} https://transpod.com/en/transpod-system/transpod-hyperloop/
Figure 7: Simplified Aerodynamics with/without an Axial Compressor

Direction of Vehicle Travel

Without Compressor

Legend

(thicker arrows correspond to a higher force)

Direction of Vehicle Travel

With Compressor
In considering the design of the system, an important distinction to draw regarding propulsion technologies is between vehicle-side and infrastructure-side propulsion systems. This decision determines whether the heavy, energy-hungry, and heat-producing propulsion system components are placed inside the moving vehicles or along stretches of the Hyperloop infrastructure.

An axial compressor-based propulsion system is always regarded as a vehicle-side propulsion system, while a linear motor can be deployed as either a vehicle-side or infrastructure-side propulsion system\(^{19}\). The distinction is based on where the power to the propulsion system is supplied from. A linear motor has elements mounted on both the infrastructure-side and the vehicle-side; one side will draw power to generate changing magnetic flux (i.e. where the motor primary is located) while the other side reacts to this changing flux (i.e. where the motor secondary/reaction plate is located). Figure 8 illustrates examples of an infrastructure-side and vehicle-side propulsion system.

**Figure 8: Simplified Comparison of Infrastructure-Side and Vehicle-Side Propulsion**

\(^{19}\) At least not in the typical very low pressure environment of around 100 Pa. See NASA’s Open-Source Conceptual Sizing Models for the Hyperloop Passenger Pod for more information: [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150000699.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150000699.pdf)
Vehicle-side Propulsion

In brief, the requisite infrastructure for a linear induction motor, the secondary (reaction plate), is a highly electrically conductive track or guideway. This could either be a metal slab (likely aluminum or copper) or a more elaborate ladder-like structure of conductors\textsuperscript{20}. The latter considerably increases efficiency, but the more complex design also increases cost. However, such infrastructure may be required if a linear induction motor is to be used for very high-speed operation (e.g. 1000 km/h or greater), as its motor’s efficiency decreases at higher speeds.

The primary propulsion element of the linear induction motor (or any linear motor) is typically a series of copper coils wound around a core structure, most often steel\textsuperscript{21}. Based on the Python modelling conducted, this is likely to account for around 5-15% of the vehicle’s total mass, depending on the core geometry and assuming that the linear induction motor is rated at full propulsive power.

The primary element is installed on the vehicle in close proximity to the conductive track (secondary element). The air gap, the distance between the primary and secondary magnetic elements, directly determines the efficiency of the motor.

Propulsion performance declines exponentially as the air gap increases, however, a very small air gap will reduce the dimensional tolerances of the track such that it cannot be practically constructed. A typical air gap for a linear induction motor would be around 10mm\textsuperscript{22}.

The main rationale for a vehicle-side propulsion system is to reduce infrastructure costs by putting all active elements in vehicles and to isolate any potential faults during operations to individual vehicles. The biggest challenge of this approach is in supplying sufficient energy to the propulsion system using components onboard the vehicle. There are two potential ways to implement energy supply to a vehicle-side propulsion system.

**Energy Transfer from Electrical Grid to Vehicle**

Energy transfer using sliding contact between a contact wire and a pantograph, as in electrified trains, is not scalable to Hyperloop speed in its current form due to the friction it creates\textsuperscript{23}. A contactless form of transfer is needed to mitigate this friction, see Figure 9 for further details. However, no such readily available solution exists that satisfies both the speed and scale of Hyperloop. Potential solutions include inductive coupling\textsuperscript{24} and the use of ionized plasma as a movable conductor\textsuperscript{25}.


\textsuperscript{25} Janzen R, ‘Plasma-Based High-Speed Power Transmission System’, USA, September 2017
Further advances in research are necessary to fully evaluate these technologies, particularly their added infrastructure cost and maintenance requirements. A small battery pack or capacitor bank would likely accompany any such system in order to smooth out power transfer variations.

**Figure 9: Vehicle-Side Propulsion System with Contactless Power Transfer**

![Vehicle-Side Propulsion System with Contactless Power Transfer](image)

**On-board batteries**

Batteries are a mature and proven technology compared with energy transfer approaches. A battery arrangement for a Hyperloop system would contain the same parts as one for an electric car, potentially with the additional requirement of pressurization\(^26\) (see **Figure 10** for further details). However, there are some challenges to using battery systems.

Batteries could increase the mass of vehicles by up to 30-50%, depending on journey time and other technology choices. Heavier vehicles require more energy to travel at the same speed and so the speed either needs to be decreased, or the power rating of all propulsion components (including the batteries) needs to be increased, which could further increase the vehicle mass.

The batteries will likely need to be charged or replaced after each journey, which delays the availability of vehicles. Furthermore, the use of battery technology indirectly increases infrastructure cost, in that the heavier vehicles require more robust infrastructure with additional charging facilities at stations.

\(^26\) Toth D, ‘Hyperloop Power Systems’, University of Edinburgh, January 2019
It should be noted that advances in battery technology (e.g. mass reduction, faster charging times) might solve these concerns, making batteries an attractive solution in the future.

**Figure 10: Vehicle-Side Propulsion System with Onboard Energy Storage**

Another important challenge posed by the vehicle-side propulsion system is thermal management. The motor(s), the electronics that drive them, and the energy transfer/storage system are all carried on-board. Each component will suffer from heat-generating losses and for the entire vehicle, particularly a battery-powered one, these losses may be in the order of a Mega Watt (MW). Notably, the surrounding low-pressure environment will also decrease the vehicle’s ability to dissipate heat through air convection (resulting in potential overheating). This increased risk of overheating increases the risk of fire inside the vehicle.

Hyperloop technology companies have indicated a couple of potential solutions that are being considered. These include:

- **Radiative cooling:** Thermal radiation allows the transfer of heat from vehicle to infrastructure without any physical contact or an atmosphere. This method is completely passive and does not consume additional energy. However, it requires a large amount of surface area to have a significant effect - existing radiative coolers achieve a radiative cooling power\(^{27}\) of up to around 100 W/m\(^2\).

  This would imply the typically smooth outer surfaces of the vehicle would not provide a significant amount of radiative cooling - the vehicle (and potentially the infrastructure) would require large passive elements to increase surface area and therefore achieve a considerable cooling power. Not only would this be challenging, it would be unlikely to fully cool a vehicle-side propulsion system and would require a supplementary or alternative cooling method, as described in proceeding bullets.

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• **Liquid cooling feeding into a large reservoir**: Heat is transferred to liquid in an onboard reservoir, warming it up. The temperature increase in the liquid can be controlled by the amount of liquid carried and the liquid could be cooled before each journey to decrease the required volume.

However, this system adds significant mass and volume to the vehicle - the liquid would likely need to be replaced frequently, increasing complexity. As this has not been discussed by any of the Hyperloop technology companies, the magnitude of its impact is not presently known. In addition, based on the type of liquid used (e.g. high thermal capacity liquids), other aspects of potential toxicity and environmental impacts would have to be further investigated and understood.

• **Liquid cooling feeding into a phase change material**: This method works on the principle of melting a material during periods of high thermal load, then later freezing/solidifying it through radiation or liquid cooling\(^28\). It is more efficient in terms of the mass and volume of coolant required than pure liquid cooling but takes away the flexibility to easily pre-cool and replace the heat storage medium between journeys. This method is likely to be more suitable for less energy-intensive applications.

An alternative solution to housing the major power-consuming units within the pod is to move them to the infrastructure side, which is akin to (the few) existing high-speed MagLev systems\(^29\).

In practice, this means installing the primary propulsion element of a linear motor (i.e. a series of coils wound around a core) into the guideway, generally across its entire length, as opposed to mounting it on each vehicle.

The cost of the primary element, in this case, will, therefore, be significantly higher than the cost of the secondary element mounted on each vehicle, whatever type of linear motor is used. And so, it makes sense that a secondary element that yields the most efficient type of linear motor should be chosen. In this case, that is a linear synchronous motor (LSM) with a secondary consisting of permanent magnets\(^30\). Refer to Figure 11 for an illustration of an infrastructure-side propulsion system.

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\(^{28}\) NASA, (2014). *Space Technology, Game Changing Development, Phase change material heat exchangers Development and Demonstration Project*

\(^{29}\) Shanghai Maglev Train / Transrapid (China), SCMaglev (Japan)

This approach has several benefits concerning energy consumption. Firstly, the greater efficiency of synchronous motors directly reduces energy consumption, with savings also arising from lighter vehicles as less mass requires acceleration. Furthermore, it could be claimed that lighter vehicles mean the infrastructure is not required to be as robust (based on the assumption that the load weight is a small proportion of the overall capsule weight), which could potentially reduce and/or place a maximum loading restriction on the guideway and provide potential economy of scale tube cost savings for a passenger-carrying system.

Secondly, higher electromagnetic efficiency also means the air gap can be increased leading to an increase in the manufacturing tolerance of the guideway, further reducing its cost and providing better protection against earthquakes. Finally, there is the benefit of centralized, synchronized control as propulsion is regulated from the infrastructure-side and shared between all vehicles, meaning any two vehicles travelling on the same motor section (which can be several kilometres long) will travel at precisely the same speed. This greatly decreases the potential of collisions and, notwithstanding potential regulatory parameters, may allow Hyperloop vehicles to be separated by very small headways.

Overall, the infrastructure-side propulsion system is markedly more efficient than the vehicle-side one but has two main disadvantages. The first is infrastructure cost, as it is more expensive to install an active motor primary into the infrastructure and connect it to the grid at regular intervals through substations.

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These substations require considerable land area, more so than railway substations, as they take on the additional role of motor control and also likely need to be closer together\textsuperscript{32}.

While the total infrastructure cost of an infrastructure-side propulsion system is almost certainly greater than that of a vehicle-side one, the propulsion system for such a system would not be the most expensive component of the Hyperloop. The tube and its supporting structures are both estimated to be of greater cost than infrastructure-side propulsion\textsuperscript{33}, with the anticipated capital cost of an infrastructure-side propulsion system being around ten times that of a vehicle-side propulsion system\textsuperscript{34}. However, the overall capital costs of a Hyperloop system are dominated by civil construction works and so the choice of propulsion system is unlikely to account for more than 15% of the overall capital costs\textsuperscript{35}.

The second disadvantage of an infrastructure-side propulsion system is fault tolerance. If a fault occurs at some point in infrastructure-side propulsion, it affects all vehicles passing through that point and will likely require a large portion of the line to shut down until a repair can be carried out - similar to a track signalling or traction power fault on a railway. On the other hand, vehicle-side propulsion faults are isolated to single vehicles, so in the event of a failure, the removal of the pod could allow for system operations to resume (at present it is not known what the recovery process for a vehicle will be, although this will vary depending on the pod design, e.g. some pods may have wheels for use in the event of a power failure). Notwithstanding that, the infrastructure-side system is intrinsically less fault-tolerant; fault occurrence could likely be reduced to statistically insignificant levels because linear motors do not contain any moving parts and are hence the most reliable method of propulsion possible.

**Intermittent Propulsion**

A promising aspect of Hyperloop technology is that the very low friction travel may allow vehicles to simply coast for the majority of their journey. In other words, Hyperloop vehicles may only rarely need to apply a considerable propulsion force, resulting in highly intermittent propulsion.

An intermittent propulsion system could offer the best of both worlds from both vehicle-side and infrastructure-side propulsion systems. It would mean vehicles could be launched and accelerated to full speed from stations using efficient infrastructure-side propulsion, then continue the rest of the journey either just coasting or maintaining speed (or reducing deceleration) with a compressor and/or a vehicle-side linear induction motor. In this case, vehicles could be brought to a stop with another infrastructure-side motor at their destination and the energy from braking recovered to the electrical grid. As most of the energy exchange, heat generation, and the greatest power draw occurs during the initial acceleration and final deceleration phases, the challenges of a vehicle-side propulsion system can be greatly reduced if it is omitted from these phases.

\textsuperscript{33} Transpod, ‘Initial Order of Magnitude Analysis for Transpod Hyperloop System Infrastructure’, Canada, 2017  
\textsuperscript{34} Colorado Department of Transportation, ‘Advanced Guideway System Feasibility Study’, USA, 2014  
\textsuperscript{35} Toth D, ‘Hyperloop Power Systems’, University of Edinburgh, January 2019
Furthermore, as infrastructure-side propulsion is only present in these phases, the associated disadvantages of higher cost and lower fault tolerance are reduced as well.

One challenge is worth highlighting for intermittent propulsion. If, as a safety measure, a vehicle has to stop between two stations where no infrastructure-side propulsion exists, it still needs to be able to relaunch itself. As this would be an emergency scenario, it is likely acceptable if vehicles cannot self-launch at the same speed as from a station. This ‘emergency propulsion’ could be provided by vehicle-side propulsion normally used to maintain speed (if present), or from a separate, down-sized emergency backup propulsion (e.g. wheels). Figure 12 illustrates an intermittent propulsion system.

**Figure 12: Intermittent Propulsion System (with Optional Compressor o/Vehicle-Side Linear Motor)**

As there are a large number of potential propulsion technologies currently under development, the technology readiness assessment will consider the following three technologies separately:

1. Axial compressor propulsion with on-board power supply
2. Vehicle-side linear motor propulsion with on-board power supply
3. Infrastructure-side linear motor propulsion connected to the electrical grid
**Axial Compressor**

As far as we are aware, full-scale electric axial compressor technologies have not been built and tested in a low-pressure tube environment.

However, technology has been studied extensively using modelling and simulations\(^3\). This study’s TRL of Hyperloop Axial Compressor Propulsion is currently estimated around **Level 3**, see Figure 13 for further details.

**Figure 13: Estimated Axial Compressor Propulsion TRL**

![Figure 13](image)

**Vehicle-side Linear Motor**

Linear induction motors (the type used in vehicle-side propulsion) as a whole are a mature technology with many commercial uses, including the Vancouver SkyTrain\(^3\). Though it is highly likely that linear induction motors have been tested by Hyperloop companies in their testing facilities, there is no publicly available information to confirm this. However, we can say with more certainty that the technology has never been tested at the maximum intended operating speed of Hyperloop and is currently only used for low-speed transportation systems up to around 100 km/h\(^3\).

Vehicle-side propulsion also raises challenges with power delivery to the propulsion system as power has to be supplied through on-board batteries or some form of contactless power transfer, neither of which have been demonstrated in an operational environment. Contactless power transfer has not been demonstrated at all for high-speed transport applications, so will not be considered in the assessment.

Using publicly available information, this study’s TRL of Hyperloop Vehicle-side Linear Motor Propulsion is currently estimated around **Level 4**, though this could be revised to Level 6 if there is confirmation that such a technology configuration has been tested at any existing test facility. See Figure 14 for further details.

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\(^3\) Coelho TMLSS, ‘Hyperloop Alpha - Conceptual study (aerodynamics)’, University of Lisbon, 2016

\(^3\) http://www.urbanrail.net/am/vanc/vancouver.htm

Figure 14: Estimated Vehicle-side Linear Motor Propulsion TRL

Infrastructure-side Linear Motor

Linear synchronous motors (the type used in infrastructure-side propulsion) are a mature technology used in all existing high-speed MagLev systems today. The whole infrastructure-side propulsion and power delivery system used in high-speed MagLev could be applied to Hyperloop with very little change.

Although there is no publicly available testing data on using linear synchronous motors in the low-pressure environment of Hyperloop, this has little effect on the integrity of the propulsion and power delivery system. The maximum operating speed of Hyperloop has not been tested with these technologies. However, the Japanese SCMaglev system has been tested up to 603 km/h with a similar or higher power consumption than that expected of a Hyperloop vehicle. For this assessment, the SCMaglev demonstration, with its many tunnels, will be considered as a relevant environment to Hyperloop, but not as a comparable final configuration of the system. As such, this study’s TRL of Hyperloop infrastructure-side Linear Motor Propulsion is currently estimated around Level 5, see Figure 15 for further details.

Figure 15: Estimated Infrastructure-side Linear Motor Propulsion TRL

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39 [https://scmaglev.jr-central-global.com/](https://scmaglev.jr-central-global.com/)
40 Toth D, 'Hyperloop Power Systems', University of Edinburgh, January 2019
3.2.5 Levitation and Guidance

As previously mentioned, the very low friction environment of the Hyperloop system may allow vehicles to simply coast for the majority of their journey, reducing the need to apply propulsion force and resulting in a significantly more energy-efficient approach than conventional MagLev technology.

Magnetic levitation allows vehicles to ‘float’ even if there is no atmosphere to provide lift. Notably, early Hyperloop concepts considered the idea of compressing air in front of the vehicle and using it to create an air bearing underneath the capsule for it to glide upon\textsuperscript{41}.

However, this approach is now considered impractical as it was estimated that vehicles would only be able to glide 0.2 mm above the guideway\textsuperscript{42}. It is likely impossible to construct and maintain guideway infrastructure with low enough dimensional tolerances to use air bearing technology safely.

MagLev technology allows for a greater air gap between the vehicle and the guideway while consuming little or no energy\textsuperscript{43} and is implemented in Hyperloop systems in two distinct ways: ElectroDynamic Suspension (EDS) and ElectroMagnetic Suspension (EMS)\textsuperscript{44}. There are many ways to implement both levitation types in a laboratory setting but only implementations scalable to a high-speed passenger transport system will be discussed here. For ease of understanding, the electromagnetic suspension will be referred to as ‘active levitation’ and electrodynamic suspension as ‘passive levitation’ for Hyperloop system applications.

In short, ‘active levitation’ is based on actively controlling the attractive force generated between a vehicle-side electromagnet or a combination of permanent- and electro-magnets and ferromagnetic (i.e. steel) guideway infrastructure to levitate the Hyperloop vehicles inside the tube. Active control is achieved through switching the electromagnets on and off thousands of times a second in controlled intervals. ‘Passive levitation’ uses vehicle-side permanent magnets or superconducting electromagnets and highly conductive guideway infrastructure that generates opposing magnetic fields through induction. These produce a stable levitation force that does not require active control as long as there is relative motion between the vehicle and the guideway.

Both previously discussed configurations of active levitation require a constant power supply. However, if the bulk of the magnetic field strength is provided by permanent magnets, then energy consumption is reduced drastically. This choice also offers slightly higher manufacturing tolerances as a greater practical air gap can be maintained with permanent magnets. In both cases, a laminated ferromagnetic structure for the guideway infrastructure will minimize levitation drag and improve efficiency. The core of an infrastructure-side motor primarily follows this structure, which means that in certain system configurations, active levitation may not add to infrastructure costs.

\textsuperscript{41} Musk E, ‘Hyperloop Alpha’, USA, August 2013
\textsuperscript{42} Coelho TMLSS, ‘Hyperloop Alpha - Conceptual study (aerodynamics)’, University of Lisbon, 2016
\textsuperscript{44} Based on Hyperloop Companies’ answers to the questionnaire
The overall capital costs of both passive levitation configurations mentioned previously are similar. While the use of superconducting electromagnets allows for higher manufacturing tolerances, it also reduces the power redundancy of the levitation system and increases vehicle mass due to additional requirements for on-board energy, as well as greatly increasing vehicle complexity\textsuperscript{45}.

Recent advancements in permanent magnet technology also mean superconductors are less likely to be the chosen technology for Hyperloop systems. In general, passive levitation has the advantage of greater manufacturing tolerance and power redundancy, but suffers from higher drag and, in many cases, more expensive infrastructure, as it is not as effectively combined with propulsion infrastructure.

The Hyperloop developers’ responses to the questionnaire showed a nearly equal split between active and passive levitation. By a small margin, the most common response was passive levitation implemented through permanent magnets.

Finally, the vehicles will also require lateral stability/guidance. Just as with levitation, electromagnetic guidance can be achieved actively or passively - but instead of providing vertical lift, it offers horizontal stability. This may be integrated within the propulsion and levitation systems or provided by a separate system in some cases. With a passive levitation system, it is beneficial to integrate guidance and levitation as both incur a considerable drag force\textsuperscript{46}.

For an active levitation system, the guidance and levitation permanent magnets and/or electromagnets are usually separated (to provide better control flexibility) and placed perpendicular to each other. If levitation elements are already mounted at an angle or horizontally (i.e. not directly on the vertical axis), then a separate guidance system may not be necessary\textsuperscript{47}. Figure 16 illustrates a simplified comparison between active and passive levitation.

\textsuperscript{45} https://www.scmaglev.com/
\textsuperscript{46} Cassat A, Jufer M, 'MAGLEV Projects Technology Aspects and Choices', IEEE Transactions On Applied Superconductivity, Vol. 12, No. 1, August 2002
The two forms of levitation and guidance discussed, active and passive, both find use in existing high-speed MagLev systems\textsuperscript{48}. Furthermore, active and passive levitation has been demonstrated in a full-sized tube by two of the Hyperloop companies. As such, this study TRL of relevant Hyperloop Levitation and Guidance Systems is currently estimated around \textbf{Level 7}, see \textbf{Figure 17} for further details.

Figure 17: Estimated Levitation and Guidance Systems TRL

3.2.6 System Topologies

The elements responsible for propulsion, levitation, and guidance can be placed in a variety of configurations within the tube. Both main types of propulsion (vehicle-side and infrastructure-side) and levitation (active and passive) can also be combined in any way. It is therefore worth highlighting that differences in placement and types of subsystems used will have a major effect on the shape of the vehicle and future interoperability of different Hyperloop systems.

Figures 16 and 18 illustrate possible combinations, including some not currently in development (note that some features are not to scale and have been exaggerated for clarity).

Three distinct cross-sectional topology types arise here:

i. Propulsion and levitation elements are placed on the vertical axis with vehicles hanging below the guideway or floating above it;
ii. Vehicles wrap around the guideway; and,
iii. All electromagnetic elements are on the horizontal axis, with vehicles gliding between them.

Note that elements may also be mounted at an angle or arc inside the tube. Think of each row in Figure 16 and Figure 18 as corresponding to a 90-degree displacement of propulsion and levitation components along the circumference of the tube - a different displacement angle is likely to result in a cross-sectional topology that can be seen as somewhere between two of the topologies shown.

Active Levitation

Active levitation creates a force where the vehicle-side magnets are attracted to the ferromagnetic guideway; this force is actively switched on and off such that the vehicle levitates at a stable height. As a result, the vehicle-side magnets cannot be placed above the guideway or float above it; instead, they hang below or between ferromagnetic surfaces.

In other words, gravity has to be pulling the vehicle-side magnets down away from the guideway so that the attractive levitation force can pull them back up.
If the magnets were placed above the guideway, they would be pulled towards it by both the forces of gravity and magnetism, resulting in the magnets sticking to the guideway.

The most straightforward solution is a topology where the vehicle hangs below the guideway (Figure 18 top row), requiring an additional lateral guidance system to ensure the vehicle does not wander side-to-side. One possible disadvantage of this topology is that it puts dynamic loads (caused by moving vehicles) on the top of the tube, rather than the bottom where it is supported by pylons. This will likely increase the structural strength requirements for the tube, potentially increasing capital costs.

A different topology may suspend the vehicle horizontally between two sides of a ferromagnetic guideway (Figure 18 middle row). This allows the elements of propulsion, levitation, and guidance to be more closely integrated, simplifying guideway construction. However, the lack of separate horizontal and vertical suspension axes is likely to make control systems more complicated and manufacturing tolerances tighter. Furthermore, this topology reduces the already limited amount of available horizontal space for the passenger compartment. In this design approach, the dynamic loads are distributed more equally around the tube compared to a top-mounted system, which can help to improve the stability of the capsules.

To mount the guideway to the bottom of the tube, where it is supported by pylons and best able to handle the dynamic loads caused by moving vehicles, the vehicle needs to wrap around it to some degree (Figure 18 bottom row). This is the only way that vehicle-side levitation magnets can be placed below the guideway. An additional lateral guidance system is required in this case to lock the vehicle’s horizontal position. While this topology reduces the structural strength requirements of the tube, it increases the design complexity of the vehicles and is likely to inhibit high-speed track-switching.

It is also important to note that the vehicle-side propulsion topologies in Figure 18 will require a power source only on the vehicle-side, while the infrastructure-side propulsion topologies require a power source on both the vehicle-side and the infrastructure-side. Shown below is this figure’s legend followed by the figure itself.

**Figure 18: Cross-Sectional Topologies with Active Levitation**
Passive Levitation

Passive levitation creates a stable lift force between the vehicle-side magnets and the conductive guideway. To utilize this force effectively, the vehicle-side magnets need to be placed above or between conductive surfaces. In this arrangement, the magnets of a stationary vehicle will be very close to the guideway. As the vehicle accelerates, the passive levitation force overcomes the force of gravity and the vehicle is lifted to create separation between the vehicle magnets and the guideway.

The most straightforward solution is a topology where the vehicle glides above the guideway (Figure 19 top row). This will require an additional lateral guidance system to ensure that the vehicle does not wander side-to-side, as well as to limit the maximum levitation height. However, this introduces an additional source of drag, which is more significant for passive levitation compared to active levitation. This is likely the least expensive topology, as the structural strength requirements for the tube are reduced by placing the guideway on the bottom, where the tube is supported by pylons.

A different topology may suspend the vehicle horizontally between two sides of a conductive guideway (Figure 19 middle row). This allows the elements of propulsion, levitation, and guidance to be more closely integrated, potentially making for a simpler guideway construction. As passive levitation and guidance are not actively controlled, the lack of independent horizontal and vertical suspension axes does not pose a challenge for control systems. In fact, the integration of levitation and guidance into the same components reduces drag, as it removes the separate guidance magnet-guideway pair. Dynamic loads are distributed around the tube but will require greater structural strength from the tube compared to a bottom-mounted system.

In order to mount the guideway to the top of the tube, the vehicle needs to wrap around the guideway to some degree (Figure 19 bottom row), this is the only way the vehicle-side levitation magnets can be placed above the guideway. An additional lateral guidance system is required in this case to lock the vehicle's horizontal position. This topology is unlikely to be implemented in a real system, as it increases both the structural strength requirements of the tube, as well as the design complexity of the vehicles. It is also likely to inhibit high-speed track-switching. Figure 19 is presented on the following page, preceded by the figure legend.

Figure 19: Cross-Sectional Topologies with Passive Levitation
For interoperability and high-speed track-switching, it is beneficial to avoid topologies that wrap around the guideway as track switches are anticipated to be carried out magnetically.

Horizontally-mounted topologies appear to have the greatest interoperability benefit while also avoiding the need for a separate guidance system, although one disadvantage may be that vehicle widths must be only slightly smaller than the diameter of the tube. As a result, the vehicles by design, become highly constrained in height, as they need to retain sufficient bypass ratio space to be aerodynamically feasible.

With Hyperloop tube diameters of only 3 to 5 metres, this could render vehicles (pods) too low for passengers to stand comfortably if there is no compressor to increase the effective bypass ratio. This means that horizontal mounting is likely to offer better compatibility with compressor-operated systems.

Little is currently known about the design and viability of high-speed track switching technologies. The only demonstration of this technology was shown by Hardt, but this had to be carried out at very low speed due to limited track length of approximately 30 metres.

Hardt’s switching technology is specific to their own configuration of propulsion, levitation, and guidance. It is understood that it will most likely not be compatible with different configurations of these sub-systems. Conservatively, this study estimates that the current TRL of this specific technology is around Level 4. See Figure 20 for further details.

**Figure 20: Estimated Propulsion, Levitation and Guidance TRL**

Other switching technologies have not been publicly discussed or demonstrated by Hyperloop companies. As such, we do not believe there is sufficient information available to assess the technology readiness level of Hyperloop switching technology at the time of this study.

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49 [https://hardt.global/technology-development/](https://hardt.global/technology-development/)
### 3.2.7 Example System Configurations

Based on the modelling conducted and confidential questionnaire responses from all known Hyperloop developers, an assessment was conducted on the three specific technology configurations likely to be implemented, without reference to any individual Hyperloop developer.

**EXAMPLE SYSTEM A**

**Description:** Infrastructure-side propulsion through a linear synchronous motor (LSM), active levitation, and guidance through a combination of permanent and electromagnets, and with the guideway mounted on the upper part of the tube such that the vehicle hangs below it.

**Advantage:** This system would likely be the most energy-efficient configuration due to the combination of high-efficiency propulsion, low-drag active levitation, and low-mass vehicle (as the propulsion system is off-board). The infrastructure-side propulsion also allows for very short headways to be synchronized, which effectively increases system capacity. This system utilizes many existing MagLev concepts and technologies within a tube environment, which likely minimizes the number of new technology advances needed to make it viable.

**Disadvantage:** The system requires an uninterrupted power source to both the infrastructure and the vehicle, for propulsion and levitation/guidance respectively. This reduces resilience, particularly as it would be difficult/costly to make the subsystems power redundant. A fault to the propulsion system could be particularly damaging, as it would likely affect every vehicle on the system. Any power loss to the levitation system would result in an immediate loss of suspension, meaning the vehicle will drop - likely onto a set of ‘landing wheels’ that require a runway on the bottom of the tube.

**EXAMPLE SYSTEM B**

**Description:** Vehicle-side propulsion through a linear induction motor (LIM) and contactless power transfer from the grid, passive levitation and guidance through permanent magnets, and with the guideway mounted on the bottom of the tube such that the vehicle floats above it.

**Advantage:** This system offers an effective and safe system for handling faults without necessarily having to carry an on-board energy source (e.g. a potentially large and heavy battery pack). The passive levitation will not halt the suspension of the vehicle if power is lost. As the entire propulsion system is provided on-board, any fault with the system is isolated to an individual vehicle. The infrastructure-side element of contactless power transfer is anticipated to be of very simple construction (a cable or rail) and hence low-cost. As a whole, the infrastructure cost of this system is predicted to be the lowest out of the three examples for short to medium distances. The bottom-mounted guideway means that a separate runway is unlikely to be required for wheeled travel (in the case of emergencies or at low speeds).

**Disadvantage:** Of the three example systems, this is predicted by the model to be the least energy efficient. The vehicle-side linear induction motor suffers from high thermal and reactive losses at high-speed; the passive levitation introduces additional drag.
Cooling the system is likely to be a major challenge, as all heat-generating components are carried on-board. Operating speeds may be lower compared to the other examples in order to reduce the thermal load on the vehicle. Contactless power transfer, while promising, has not been validated at scale. The small air-gap required for the efficient operation of the vehicle-side linear induction motor reduces the manufacturing tolerance of the guideway, making for difficult construction.

**EXAMPLE SYSTEM C**

**Description:** Intermittent propulsion such that vehicles are launched and stopped by infrastructure-side linear synchronous motors (LSM) around stations and coast with the aid of an axial compressor otherwise. Active levitation is achieved through a combination of permanent electromagnets with the guideway mounted at both sides of the tube.

**Advantage:** The modelling suggests this is the optimal system for long-distance coasting and provides a middle ground between the two previous examples. Energy efficiency is likely comparable to System A due to the initial launch from infrastructure-side propulsion, low-drag active levitation and further drag reduction of the axial compressor. Fault tolerance on the infrastructure-side is comparable to System B for the majority of the journey, except near stations where there is infrastructure-side propulsion - here it is more comparable to System A. This system may have the lowest capital cost for long-distance travel. The side-mounted guideway topology means that such a system can be (though is not necessarily) interoperable between any type of propulsion or levitation.

**Disadvantage:** The high complexity of this system is likely its largest disadvantage, with the risk of vehicles becoming considerably more expensive and less fault-tolerant compared to the other examples. Further resources are needed to mitigate the risk of vehicles getting stuck in a part of the tube where there is no infrastructure-side propulsion. Although overall energy efficiency is quite good, some energy is wasted on carrying the additional onboard weight and the lower efficiency of the compressor. Construction of a separate guideway may be required towards the bottom of the tube for emergency wheeled travel. The presence of a compressor will likely require headways between vehicles to be increased due to the turbulence created in the tube.

On the proceeding page, **Table 5** compares the three example systems based on their performance against energy efficiency, infrastructure cost, vehicle mass/cost, fault tolerance, and air gap. In summary, the table below shows that at present, no one approach has a clear advantage over the other two and for each example system there is more than one area of weakness requiring further development.

The application and design of the three approaches are all subject to ongoing development by the technology providers, and as the components and systems evolve through further testing and refinement the comparative advantages of the different approaches may change.
Table 5: Comparison of the Example Systems (red is worst, green is best)

<table>
<thead>
<tr>
<th>Example System</th>
<th>Energy Efficiency</th>
<th>Infrastructure Cost</th>
<th>Vehicle Mass / Cost</th>
<th>Fault Tolerance</th>
<th>Air Gap</th>
</tr>
</thead>
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<td>A</td>
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<td></td>
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<tr>
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<td>C</td>
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</tbody>
</table>

3.2.8 Acceleration

Table 6 shows the estimated time and distance required to achieve maximum velocities at different constant rates of acceleration. Note that the same values may apply when considering the time and distance required to brake from maximum velocities at different constant rates of deceleration.

The calculations are computed using Newton’s Equations of Motion. This relationship is plotted and shown in the two graphs in Figure 21.

Table 6: Acceleration Rate versus Time and Distance to reach Maximum Velocity

<table>
<thead>
<tr>
<th>Acceleration (G-Force)</th>
<th>600 km/h</th>
<th>800 km/h</th>
<th>1000 km/h</th>
<th>1200 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time* (s)</td>
<td>Distance* (km)</td>
<td>Time* (s)</td>
<td>Distance* (km)</td>
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<td>17</td>
<td>2</td>
<td>23</td>
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</tbody>
</table>

* Rounded up to the nearest second and kilometer
### 3.2.9 Operations

The passenger experience inside a Hyperloop vehicle should not be much different from modern air or rail travel (perhaps somewhere between the two), as the accelerations experienced by passengers will be limited by requirements for comfort, not by technology capability.

In general, acceleration in any direction will likely be limited to around 0.1 G\textsuperscript{50} and so reaching a speed of 250 m/s will take just over 4 minutes over a distance of 31 km. However, in emergency scenarios, this acceleration (or deceleration) could be greatly exceeded.

If passengers are not required to wear seatbelts throughout the journey, emergency braking rates of around 0.4 G\textsuperscript{51} are reasonable, with vehicles coming to a stop in roughly 45 seconds. Whereas if seatbelts are required, emergency braking could exceed 1 G\textsuperscript{52} and vehicles could be brought to a stop in around 20 seconds.

At present with no regulations in place it is not clear what the expectation will be regarding seatbelts, as airplanes currently require seatbelts, while trains do not, both options continue to be discussed. However, the impact of such forces on the human body will need to be further explored in order to understand appropriate comfort levels and to avoid the creation of unforeseen hazards, for further detail refer to Section 4 – Regulatory Regime for Hyperloop.

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While the linear infrastructure of Hyperloop systems is generally more space-efficient than that of railways and roads, its stations/terminals may need to be quite large so that they do not become a major bottleneck. With vehicles leaving the stations as frequently as every 18 seconds according to questionnaire responses from Hyperloop developers, it is unrealistic to fully board and depart a vehicle in that short timespan.

Hence, a single Hyperloop tube will likely require many ‘boarding gates’ operating in parallel and merging into the same track - very much akin to how an airport runway is operated (discussed further in Section 3.3). The boarding gate infrastructure is further complicated by the need for an airlock or seal system (portal) to keep the tubes under low pressure.

A promising aspect of Hyperloop technology is that individual vehicles may never need to make intermediate stops. In other words, the small, frequent and autonomous vehicles allow for on-demand travel. This doesn’t mean that a Hyperloop tube cannot connect several points on a line, it just means that the track needs to briefly split and diverge around an intermediate point.

As a result, other vehicles can speed past intermediate points without ever slowing down, saving travel time. This will come with technical complications, particularly, the need for a high-speed track-switching capability. Figure 22 illustrates the accelerating, coasting, and braking operations on a Hyperloop line with and without an intermediate diversion.

**Figure 22: Hyperloop Line with Intermediate Diversion**

3.2.10 Audible Noise

There is no available data for the maximum audible noise generated by any Hyperloop system, as no testing facility long enough currently exists to carry out full-scale, full-speed tests. A fair comparison cannot be made between Hyperloop and MagLev technologies as it has been with electromagnetic noise, as both the maximum speed and aerodynamic environment differ greatly.
Some researchers have identified infrastructure vibrations as a potential issue with Hyperloop but concluded that this will ultimately depend on the span between support pylons\textsuperscript{53}.

There are, however, several aspects of Hyperloop technology that act to considerably dampen the noise generated by vehicle travel:

1. Vehicles are not in physical contact with the infrastructure and hence there is no ‘wheel noise’ and vibrations are dampened. But due to the stiff nature of magnetic levitation, some vibrations will still be measurable on the infrastructure-side, with the larger the air gap the lesser the effect. It should be noted that in case of an emergency, the vehicles may come in contact with the infrastructure causing potential noise.

2. The vehicles and the infrastructure are separated by a low-pressure, generally near-vacuum environment. Although it is common knowledge that sound does not travel in a vacuum, that is not applicable in this case. When travelling at full speed a considerable amount of air is pushed to the small space between the vehicle and the tube (and/or is compressed through the vehicle), some aerodynamic ‘whooshing’ sound is possible and could be audible from the outside, although further testing of the concept is required to fully understand how this will compare to an open-air system.

3. Any sound generated inside the tube will likely be heavily dampened by the thick tube walls.

4. Hyperloop infrastructure is generally elevated from the ground, or buried underground, adding some vertical distance where the sound can dissipate. Additional damping is provided by the soil if the system is underground, while it is also possible for raised pylons to include sound barriers (similar to many existing high-speed railways).

The vacuum pumping stations maintaining the low-pressure environment within the tube would be a source of constant noise. However, it has been suggested by the Hyperloop technology companies that these can be housed in such a way that noise is sufficiently reduced.

### 3.2.11 Electromagnetic Noise

Electromagnetic fields (EMFs) can be split into electric and magnetic fields, both of which can be further split into static and varying. Electric fields create live potentials (voltages) around their source, but these are quickly discharged in the presence of a grounded conductor\textsuperscript{54}. As Hyperloop infrastructure is tethered to the ground, electric fields can be easily mitigated at little-to-no additional cost.

A metallic shell surrounding the vehicle will alleviate electric fields inside the passenger compartment, while structural steel elements of the tube are likely to play a similar role. Magnetic fields are the main concern then, as mitigating them comes with greater difficulty and significant trade-offs.

\textsuperscript{53} Alexander N A, Kashani M M, 'Exploring Bridge Dynamics for Ultra-high-speed, Hyperloop, Trains', Structures vol. 14, June 2018

\textsuperscript{54} Energy Networks Association, 'Electric and Magnetic Fields', United Kingdom, 2017
Static magnetic fields are those whose strength does not vary with time – a typical example is a permanent magnet.

These types of fields are not at all dangerous to the human body, except in extreme laboratory settings\(^{55}\). As such, general public exposure limits are set to 400 mT (milli-Tesla) by the International Commission on Non-Ionising Radiation Protection (ICNIRP). The risk with static magnetic fields is that they create attraction forces to ferromagnetic materials, which can cause injuries due to flying ferromagnetic objects\(^ {56}\), and is particularly dangerous to persons with implanted medical devices.

These considerations lead to much lower restriction levels, generally around 0.5 mT\(^ {57}\). The strength of static magnetic fields quickly decreases with distance, so these are only an issue inside the vehicle\(^ {58}\). It is possible to decrease the outward strength of static magnetic fields by surrounding the source with a magnetically permeable material (such as steel), but the amount of material needed is far greater than for the mitigation of electric fields. As a result, this option can increase the weight and cost of the vehicle significantly\(^ {59}\).

Varying magnetic fields are ones whose strength varies over time (i.e. caused by a conductor that has alternating current flowing through it) – this means that they induce electrical currents in surrounding objects, or in other words, they induce an internal electric field in the objects. This can have several negative effects, including:

- Creating noise in data transmission, whether wired or wireless (except for optical communication)
- Adverse effects on the human body arising from transient nervous system responses
- Induction heating of conductive objects

At lower electrical frequencies (1 Hz - 100 kHz), such as those generated by Hyperloop’s propulsion / levitation systems, the ICNIRP estimates that a peak magnetic flux density of around 1-2 mT is required to begin causing adverse effects for passengers\(^ {60}\).

There is practically no land-based (only maritime) communication in this frequency range today\(^ {61}\), so the noise is likely to have little impact on communication channels. If necessary, parts of Hyperloop infrastructure in the close vicinity of medical or military facilities could be installed with additional magnetic shielding. Whether this will be necessary remains to be confirmed by testing.

\(^{55}\) INCIRP Guidelines, ‘On Limits of Exposure to Static Magnetic Fields’, Health Physics, 2009
\(^{56}\) INCIRP Guidelines, ‘On Limits of Exposure to Static Magnetic Fields’, Health Physics, 2009
\(^{58}\) Kircher R et al, ‘Electromagnetic Fields Related to High Speed Transportation Systems’, Transportation Systems and Technology, 2018
\(^{59}\) Kircher R et al, ‘Electromagnetic Fields Related to High Speed Transportation Systems’, Transportation Systems and Technology, 2018
\(^{60}\) INCIRP Guidelines, ‘On Limits of Exposure to Static Magnetic Fields’, Health Physics, 2009
\(^{61}\) Ofcom, ‘Frequency Allocation Table’, United Kingdom, 2017
There is no available data on the amount of electromagnetic noise generated by specific Hyperloop systems and as such, its impact cannot be fully assessed at present. Electromagnetic noise that could be harmful to sensitive devices (such as equipment in hospitals) will likely be produced in parts of the system.

However, shielding technologies could be used to prevent the noise from escaping outside the tube, or entering into the passenger compartment. To validate the electromagnetic safety of a Hyperloop system, a testing facility that operates at both the full power and speed of a commercial system is needed.

Although there are currently no such full-scale Hyperloop systems to assess, a relevant comparison can be made to existing MagLev technologies, as these use similar or identical technologies for the propulsion and levitation of vehicles. Table 7 summarises the maximum measured static and varying magnetic fields of existing high-speed MagLev systems in China (TR-07), Germany (TR-08) and Japan (SCMaglev).

Table 7: Maximum Measured Static and Varying Magnetic Fields

<table>
<thead>
<tr>
<th>Field and Locations</th>
<th>China (TR-07)</th>
<th>Germany (TR-08)</th>
<th>Japan (SCMaglev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor Level</td>
<td>--</td>
<td>0.26 mT</td>
<td>--</td>
</tr>
<tr>
<td>Seat Level</td>
<td>0.1 mT</td>
<td>0.12 mT</td>
<td>20 mT</td>
</tr>
<tr>
<td>Varying Field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor Level</td>
<td>--</td>
<td>0.024 mT</td>
<td>--</td>
</tr>
<tr>
<td>Seat Level</td>
<td>0.004 mT</td>
<td>0.006 mT</td>
<td>0.01 mT</td>
</tr>
<tr>
<td>A distance of 1.5 m outside the vehicle</td>
<td>--</td>
<td>--</td>
<td>0.2 mT</td>
</tr>
</tbody>
</table>

Technology choices and their implementation can have a major effect on measured magnetic fields. The systems in China and Germany are both based on the Transrapid design and only have minor differences. The difference are in both the design and measured magnetic fields, although these measurements fall well within regulations and are comparable to those of some railways.

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64 Brecher A et al, ‘Electromagnetic Field Characteristics of the Transrapid TR08 Maglev System’, Germany, 2002
65 Nakagawa M et al, ‘EMF Issues with Maglev in Japan’, Japan, 1993
The Japanese SCMaglev system, on the other hand, has static magnetic fields in some parts of the vehicle that could potentially be dangerous to people with certain implanted medical devices\textsuperscript{68}. This is largely due to the use of superconducting electromagnets at a large air gap in the combined propulsion/levitation system, rather than the traditional electromagnets at a small air gap used in the Transrapid systems\textsuperscript{69}.

It should, however, be noted that the Japanese system is still at an experimental stage and the high static magnetic fields are a known issue that is being addressed through research into magnetic shielding technologies. Solid steel as a shielding material has proven impractical, due to the excessive weight it adds to the vehicle\textsuperscript{70}.

It is expected that, thanks to the lower per-vehicle power consumption\textsuperscript{71} and the enclosed environment of the tube, the electromagnetic noise generated by Hyperloop (both inside the capsule and outside the tube) will be somewhat lower than that of existing MagLev systems. However, this cannot be stated with certainty at this time.

Electric fields are easily mitigated in ground-based transportation systems. The main concern facing Hyperloop companies is that of static magnetic fields in the passenger compartment, particularly if there are passengers with medical implants. Shielding technologies exist that can reduce these fields, but may add substantial weight to the vehicles, decreasing energy efficiency and increasing overall cost.

The impact of magnetic fields on areas surrounding the Hyperloop infrastructure is unknown. However, we note that this is not an issue with existing MagLev systems and all the Hyperloop companies participating in the questionnaire indicated they do not foresee the need for additional electromagnetic shielding outside of the tube. Finally, it is expected that Hyperloop will be unlikely to interfere with existing communication channels, as the frequency of the noise generated is too low.

3.2.12 Additional Considerations

Based on the analysis set out in this section and the aggregated questionnaire responses from all known Hyperloop developers, the following new findings can be reported:

- There is a difference of opinion among Hyperloop developers regarding some key statistics, for example:
  - The average vehicle mass for a capsule is circa 20 tonnes (based on a 47 passenger-carrying capacity), however, the actual pod weights vary significantly between different designs.

\textsuperscript{68} Fukata M et al, ‘Influence of Electromagnetic Interference on Implanted Cardiac Arrhythmia Devices In and Around a Magnetically Levitated Linear Motor Car’, Journal of Artificial Organs, 2005
\textsuperscript{70} Kircher R et al, ‘Electromagnetic Fields Related to High Speed Transportation Systems’, Transportation Systems and Technology, 2018
\textsuperscript{71} Toth D, ‘Hyperloop Power Systems’, University of Edinburgh, January 2019
- The estimated headways currently being discussed vary from 18 seconds to several minutes, with an average of these being about 120 seconds.

- Equally, Hyperloop developers have estimated the average system could transport as many as 6,500 passengers per hour, depending on pod capacity and headway. However, with significant differences between developers in pod capacity and possible headways, the possible hourly capacities range significantly.

Table 8 identifies that the actual range could vary from 300 to 16,000 passengers per hour, one way, depending on the combination of headways and pod capacity. It should be noted that no scenarios reflecting both maximum pod capacity and minimum headways were identified by developers. This suggests that the true capacity is likely to be weighted towards the lower end of the range, as seen in the suggested average hourly one-way capacity.

<table>
<thead>
<tr>
<th>Departure Headway (seconds)</th>
<th>18</th>
<th>30</th>
<th>60</th>
<th>120</th>
<th>180</th>
<th>240</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Departures per hour</td>
<td>200</td>
<td>120</td>
<td>60</td>
<td>30</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Capacity (Seats)</td>
<td>20</td>
<td>4,000</td>
<td>2,400</td>
<td>1,200</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>8,000</td>
<td>4,800</td>
<td>2,400</td>
<td>1,200</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>12,000</td>
<td>7,200</td>
<td>3,600</td>
<td>1,800</td>
<td>1,200</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>16,000</td>
<td>9,600</td>
<td>4,800</td>
<td>2,400</td>
<td>1,600</td>
</tr>
</tbody>
</table>

- On average, the maximum operational speed proposed by the Hyperloop developers is stated to be anywhere from 1000 – 1200 km/h. However, as noted in the Literature Review, early Hyperloop systems are not expected to be tested and certified for commercial operation at these speeds. There is currently no established timeframe for when Hyperloop companies envision testing at these higher speeds.

- The Hyperloop tube is most likely to be made of steel and measure three (3) to five (5) metres in diameter.

- The most common technology choices are an infrastructure-side or intermittent propulsion system, on an axial compressor and a passive levitation system, although it was observed that all of the possible technology choices outlined in this section are in development. The likely explanation for this propulsion choice is the challenge identified in supplying sufficient energy to a vehicle-side propulsion system. Therefore, it is expected that early Hyperloop systems will likely use some form of infrastructure-side or intermittent propulsion.

- High-speed track-switching technology, combined with the small and frequent vehicles, may allow Hyperloop passengers to skip intermediate stops. However, this type of technology is yet to be proven at scale.
3.2.13 Engineering Review Conclusions

In this section, we revisit the Technology Readiness Level (TRL) of key constituent technologies within a Hyperloop system using published information and expert judgement. We also augment the existing literature and other public studies by analyzing some of the different options available for key constituent technologies (e.g. propulsion, levitation/guidance, and power delivery) to reflect the significant differences in the technology that each Hyperloop company intends to commercialize. Table 9 provides a summary of the assessment provided in this study through the lens and perspective of the TRL’s.

Table 9: A Summary of the Technology Readiness of Hyperloop Components

Based on all available information, some key constituent technologies can be classified as TRL 7, but the technology as a whole cannot because the infrastructure required has not yet been built and tested by any Hyperloop company over long distances. However, we note that the Hyperloop companies using infrastructure-side linear motors as their propulsion technology start at an advantage as this has been proven at relatively high speeds in existing MagLev systems, while other types of propulsion technologies such as vehicle-side linear motors and axial compressors have not.

Policymakers must understand that the different approaches taken by each Hyperloop company will yield Hyperloop technologies that vary substantially in terms of passenger or freight capacity, capital and operational costs, energy efficiency, safety needs, and other parameters. In time, these approaches may converge due to market forces or regulatory standardization within Europe or North America.

As identified through this section, the technology differences of the various Hyperloop system components are significant enough that Transport Canada should not seek to assign a blanket TRL to Hyperloop technology. Instead it is possible to distinguish the level of readiness of each Hyperloop company’s proposed technology using a simple assessment (see example in Table 10) to identify where gaps and uncertainties exist.
### Table 10: Example Assessment

#### Technology Development

- What type of propulsion, levitation/guidance, and power delivery technologies will they use?
- What type of tube, vehicle, pressure management, and switching technologies will they use?
- Which individual aspects of their technology are new or have not yet been prototyped or used in other high-speed transportation systems?

#### Testing Facility Development (0.5-5 km)

- Have they secured sufficient funding to implement a testing facility of at least 0.5 km?
- If so, what is the location, length, and maximum operational speed of their testing facility?
- When is their initial testing facility likely to be operational and how long will testing last?

#### Certification Facility Development (15-50 km)

- Have they secured sufficient funding to implement a certification facility of at least 15 km?
- If so, what is the location, length, and maximum operational speed of their certification facility?
- When is their certification facility likely to be operational and how long will certification take?

From Transport Canada’s perspective, the main purpose for examining each Hyperloop company’s technology development should be to determine if they are developing a technology similar to existing high-speed Maglev systems (with the addition of a vacuum tube) or something more novel requiring greater research, testing, and validation before it can be commercialized.

Understanding each Hyperloop company’s plans to develop a testing facility is one critical final proof of concept for their technology. Here, the performance of various constituent technologies is validated in an operational environment and different variations can be tested to find the best solution. The testing facility also offers an opportunity to identify cost-saving measures before a longer track is built.

We anticipate that this facility should be able to test operations at a high speed (> 400 km/h), though not necessarily the maximum operational speed of a commercial system.

Lastly, each Hyperloop company will need to develop or co-develop a certification facility to certify that their technology is safe for commercial operation. At this stage, every aspect of each Hyperloop company’s technology needs to be demonstrated to the same specifications as a commercial system. This facility will likely require several tracks that vehicles can switch between while travelling at high speed as well as changes in the horizontal/vertical directions and some type of emergency provision.
We believe that the level of readiness of each Hyperloop company’s technology should correlate closely with the detail and completeness of their responses to this type of assessment. Furthermore, it is advised that the failure of a Hyperloop company to answer questions regarding the types of technology they use and their plans to test them may indicate they are still in the research phase and their technology is not ready for deployment.

3.3 Concept as a Dominant Passenger Transportation Mode for Intercity Travel

The concept of Hyperloop was first conceived as an alternative to high-speed rail, specifically to provide a connection between San Francisco and Los Angeles for passengers. Although concerns remain about system operation and the ability of the human body to handle such conditions, the target market for Hyperloop is still envisioned to be passengers/commuters. Several transportation modes offering different travel experiences already exist, each with its own benefits. This section will explore what the travel experience with Hyperloop might look like and compare it to other transportation modes serving similar trip types.

Commuters modify their travel behaviour in response to changes in available transportation options. The history of urban development shows that when a faster, affordable, and reliable transportation technology option is introduced, location choices for essential urban activities are expanded as commuters choose to travel further. The last major disruptive commuting transportation that made more distant locations possible was the North American freeway system, introduced in the 1950s and giving rise to the metropolitan suburbs.

3.3.1 Trip Types

Limited analysis has been published to date regarding the types of users a Hyperloop system may attract. When first conceived, the technology was envisaged as a cheaper, more efficient, and more environmentally friendly alternative to high-speed rail, with commuters being the largest beneficiary demographic. Projected journey times of 30 minutes between city pairs within 500 to 600 km at travel speeds approaching 1,200 km per hour, would enable travelers to commute to an adjoining metropolitan region and return the same day.

However, as interest and understanding increased, other possible applications of the technology were explored. As well as a competitor to high-speed rail, Hyperloop has been identified in several feasibility studies\(^2\) as a viable alternative to short-haul air travel.

As a means of comparison, the top safe operating speeds of a range of transportation modes are identified in Table 11. The information provided in this table is based on calculations and publicly available information.

\(^2\) Virgin Hyperloop One. (2019). Missouri Hyperloop Feasibility Study
### Table 11: Comparison of Speed, Acceleration and Headway for various Transportation Modes

<table>
<thead>
<tr>
<th>Compared Items</th>
<th>Hyperloop</th>
<th>Air&lt;sup&gt;8&lt;/sup&gt;</th>
<th>MagLev</th>
<th>High-Speed Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Speed</td>
<td>1000~1,200 km/h</td>
<td>1,049 km/h</td>
<td>450 km/h</td>
<td>350 km/h</td>
</tr>
<tr>
<td>Initial Acceleration</td>
<td>9.8 m/sec</td>
<td>5 m/sec&lt;sup&gt;*&lt;/sup&gt;</td>
<td>2 m/sec</td>
<td>2.6 m/sec</td>
</tr>
<tr>
<td>Headway</td>
<td>As low as 18 seconds&lt;sup&gt;n&lt;/sup&gt;</td>
<td>45 seconds&lt;sup&gt;^&lt;/sup&gt;</td>
<td>NA</td>
<td>240 seconds&lt;sup&gt;µ&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>8</sup>Analysis is based on the reported performance of a Boeing 787

<sup>*</sup>Based on the average time taken to accelerate from stationary to cruising speed, as the rate varies between the runway and airborne

<sup>n</sup>The Technology companies have provided a range of different headways, with 18 seconds being the lowest provided but this is all based on simulations at this stage of development

<sup>^</sup>Based on the results of calculations regarding runway length and airport capacity set by Transport Canada that are used to calculate the separation time between departures on a runway

<sup>µ</sup>Estimate based on the cruising speed of the service and braking distance

The above table indicates the anticipated maximum speed of Hyperloop to be between 1000 and 1200 km/h (depending on the technology company), making it significantly faster than alternative ground-based modes. Additionally, the design of the Hyperloop system would allow for less time spent accelerating and decelerating to and from cruising speed compared to the other modes. The table also identifies the speed of acceleration for Hyperloop as more than four times that of other ground-based modes and almost double that of air which, given the top operating speeds, suggests it is capable of reaching ‘cruising speed’ in the shortest time of all the modes. This is based on an acceleration tolerance of 0.1 G.

However, several Hyperloop technology companies acknowledged they are designing capsules based on a 0.2 G acceleration parameter<sup>73</sup>. At this tolerance level, the time to ‘cruising speed’ would be further reduced, providing an even greater advantage over other modes.

Along with operating speeds and accelerating/decelerating standards, the anticipated headways of Hyperloop are also expected to be considerably smaller than alternative modes. While no information on headway testing has been released to date, Hyperloop companies have indicated the headways could be as small as 18 seconds. These estimates are untested and based solely on simulations, therefore it is not possible to assess their feasibility. However, the feasible headway of the system will be affected by the type of propulsion and power supply technologies employed, as this will impact the safe braking distances and the ability to implement a widespread shutdown of the system simultaneously as opposed to on an individual capsule level. Given these factors, it is conceivable that different headway standards will need to be developed for certain design specifications.

<sup>73</sup> Based on interviews with the Hyperloop Technology Companies
If this optimal headway is considered in comparison with the alternatives of air and rail, it performs well. Canadian Aviation Regulations require a 45-second headway between aircraft takeoffs\textsuperscript{74}, and railway guidance requires a headway of suitable length to allow for braking distance of the consist\textsuperscript{75}.

If Hyperloop has the potential to offer the fastest speeds, shorter periods at slower speeds, and smaller headways, this could provide a travel option more appealing to potential users than existing modes. Of the characteristics that determine mode choice, shorter travel times are prioritized\textsuperscript{76}. This would suggest a significant shift from alternative modes if Hyperloop was introduced into an existing transportation corridor, as several Hyperloop companies have suggested in various corridor studies\textsuperscript{77}.

Although identified as the fastest mode of those evaluated, there are still many other factors to consider when evaluating the type of trips that might utilize Hyperloop. Other travel attributes also play a significant role: door to door journey time, travel cost, level of service, and reliability.

While a Hyperloop system can theoretically transport commuters between Toronto and Montreal from station to station in 30 minutes, this would not include travel time from home to the Hyperloop station or passenger processing at the station, especially if safety and security regulations require passenger and baggage screening. Neither does it include travel time to the final destination from the arriving pod station. If, as many Hyperloop technology proponents envisage, there is one central metropolitan location for a Hyperloop station, situated in the downtown core, access and egress times could be considerable, especially during peak periods.

In terms of travel costs, with so many significant factors not yet fully realised, any discussion of costs is largely speculative. Inasmuch as can be considered, travel costs are explored in the economics section of this report.

For commuters, level of customer service is typically limited to safe, secure, and reliable travel with limited on-board-services. Considering the maximum trip time for a Hyperloop, there would likely be little time to provide for meals, beverages, or even workstations.

Reliability is a critical attribute for commuters. When reliability is compromised, urban activity choices are reduced to less distant locations and economic losses are incurred. Reliability attributes, such as frequency of service, ticketing/reservation systems and capacity, would need to be addressed by Hyperloop designers.

Additional aspects of the travel experience considered by travelers when selecting modes include window proximity, internet access, comfort, on board services, etc. Hyperloop is unlikely to offer external views due to the high speed being potentially disorientating and the added design complexity transparent materials would bring. As with any new technology, a limited proportion of the population will be early adopters and this is likely to be particularly true for Hyperloop given the concerns regarding the health and safety impacts of travelling at such speeds.

\textsuperscript{74} Transport Canada. (2020). Canadian Aviation Regulations (SOR/96-433)
\textsuperscript{75} Transport Research Board. (2017). Transit Capacity and Quality of Service Manual, 3rd Edition
\textsuperscript{76} Rundmo, T et al. (2011). The role of risk perception and other risk-related judgements in transportation mode use
\textsuperscript{77} Hyperloop Transportation Technologies. (2019). Great Lakes Hyperloop Feasibility Study
There remains a proportion of the population that will not travel by airplane due to safety concerns and fears, so it can be expected that not everyone will be comfortable travelling by Hyperloop. It should be noted that other factors, such as security clearance and time to depressurize and re-pressurize tubes, could potentially affect Hyperloop total travel time from start to finish. Beyond very quick journey times and a high frequency service, it is undefined how Hyperloop would compare in terms of affordability, ease of use, flexibility, and reliability to current commuting transportation options.

In reviewing the common factors determining trip modal choice, journey time and price are the two most prevalent. Hyperloop offers the fastest mode for travel between two points and would be attractive based on the journey time savings it can offer. However, price will play an important role in determining the type of users that chose the service. In the present market, airlines offer the fastest travel times but, due to factors such as fuel consumption, supporting infrastructure, and unit cost, they are most often the most expensive mode. This means only consumers who place the most value on journey time savings would be prepared to use such a mode, when other alternatives exist. At present, the exact costs involved in the construction and operation of Hyperloop are not known, and so the price point of the service cannot be confirmed (Section 5 - Estimates of Capital and Operating Costs provide further information on these possible costs). The system costs, along with the capacity, will likely determine ticket price which, in turn, will influence the type of user.

Due to the significant number of remaining uncertainties, it is not yet clear exactly where the preferred environment for the implementation of a Hyperloop system will be. There is however, growing interest from Hyperloop technology companies in exploring intercity travel. It was noted in interviews that many of the technology companies envision their systems competing with high-speed rail, MagLev, and short-haul air travel. Such markets are traditionally split between business travel during weekdays and recreational travel on weekends. Several studies undertaken have examined specific intercity corridors in order to compare existing options with Hyperloop and assess the comparative advantages of the service. Many of these studies noted significant user travel time savings, which are anticipated to not only encourage modal shift away from existing modes but also provide sufficient incentive to induce additional demand. These assessments were conducted using expected operating speeds, which are a key component of the analysis findings. However, until these are realized it is difficult to know the actual impact.

As the Hyperloop concept has continued to evolve and develop, further applications beyond the inter-city connection have been explored. One of the areas that has seen growing interest from technology developers and potential investors is the idea that Hyperloop could serve as a long-distance transit service for some major urban areas. Several studies, such as the recently published Great Lakes study, have suggested that Hyperloop routes might have several stops between major urban centres. This raises questions regarding whether all services would stop at all locations, or whether certain stations may be bypassed in order to preserve maximum travel time savings. These questions remain outstanding, however the idea of a neighbouring town previously outside of the traditional commuter belt, having a Hyperloop connection that reduces travel time to below an hour has generated significant interest.
The concept is still in the early stages with the focus to date on the engineering challenges of Hyperloop. Questions regarding how bookings, security, schedules and other matters common to established transit modes still need to be addressed. However, the idea of expanding the catchment area of major urban areas through improved technology and transportation connections is well established. Given the relatively new idea of Hyperloop as a commuter transit system there are many questions still to be resolved, however, the interest of smaller towns in having a Hyperloop station is already visible in several locations where proposed corridors exist.

The corridor studies completed to date have looked at a number of different routes around the world, ranging from 'short' 300-500 km corridors up to 1500 km corridors. If Hyperloop technology can ultimately achieve the suggested top speeds, it could mean that journeys of 1500 km might take little more than an hour to complete. If the potential to offer these significant journey time savings to passengers is realised, Hyperloop would offer a faster way to travel these distances than any other existing transportation mode.

3.3.2 Experience

The user experience will play a significant role in establishing the range and type of service the Hyperloop system might provide. To date, the design and testing of the various Hyperloop companies’ capsules has focused on proof of concept and testing maximum velocities, as opposed to internal design. Significant speculation remains regarding the capsule interior. **Exhibit 3** shows a pair of conceptual designs for the possible internal layout of a Hyperloop pod. At present, very little has been confirmed about the interior design. There is still no guidance on whether the pods will allow passengers to stand and move around, or whether they will need to be seated at all times. Equally, no discussion on the possibility of amenities such as restrooms, tables or WIFI exists in any detail.

**Exhibit 3: Conceptual layouts developed for Hyperloop passenger pods**
The designs do not suggest provision for onboard facilities, which would limit the distance such services could travel. Additionally, in contrast with airplanes and trains, the Hyperloop companies did not indicate any intention to provide onboard services such as meals or refreshments. While the images above include well-supported seats with seatbelts to protect passengers from the effects of rapid acceleration and deceleration, seat design and safety considerations for passengers are issues that still require testing at high operating speeds.

### 3.3.3 Terminals

Limited research and design has taken place on the requirements and layout of a Hyperloop terminal. At present, one of the only known publicly available designs of a potential Hyperloop terminal that considers operational functionality as well as design has been produced by Virgin Hyperloop One, which they have called a ‘Hyperportal’ and posited could be developed in Dubai. Several other conceptual designs have been considered, most notably the proposed design of the Mumbai (India) terminal, which imagines integrating the station into the existing urban environment. Exhibit 4 shows the conceptual renderings of an internal and external layout of a Hyperloop terminal.

**Exhibit 4: Conceptual Images developed for Hyperloop Terminals**

![Conceptual Images of Hyperloop Terminals](image)

The internal design and arrangement of Hyperloop terminals will depend on security and boarding requirements legislated for the technology. If security screening for passengers and luggage is required, then larger terminals will likely be necessary to accommodate these services. Additionally, if Hyperloop does have headways of just 18 seconds (the shortest identified headway), multiple boarding areas will be required to accommodate this level of service, further expanding the station footprint.

This could lead to a large ‘platform’ area where multiple capsules can load and unload simultaneously before being positioned for entrance into the tube. As boarding and alighting will need to happen in an area with regular pressure suitable for humans, an airlock (also referred to as a ‘hatch’ or ‘portal’) of some description will be needed between the platform area and the tube itself, requiring sufficient space to handle the volume of passengers while remaining a safe and secure environment.

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79 Electrek. (2016). *Hyperloop One unveils the design of its terminal or ‘Hyperportal’*

80 Amazing Architecture. (2019). *Hyperloop terminal designed by Astin John*
How loading and unloading of pods will happen is still unclear. Concepts have included boarding in a similar manner to airplanes, with pre-booked assigned departure and seating numbers, or using an on-demand approach where a pod would depart once full.

For simple networks with very few destinations the on-demand approach may be more effective. However, more complex Hyperloop networks may necessitate a booking system.

Terminal design is still very much at the conceptual stage and the same is true regarding optimal central urban and regional locations. While some feasibility studies have considered the optimal location for a Hyperloop terminal, there is still the expectation that a central location within urban areas will attract the highest level of ridership.

Many imagine that due to Hyperloop acting as a higher order transit mode\(^\text{81}\), it will need to be situated in an easily accessed location, such as the convergence point for local transit, which would likely place it in the downtown area. Land is at a premium in most urban centres and suitable sites for a terminal will be limited and likely require the redevelopment of existing land uses. In some instances, this might present an opportunity to increase land use intensification, equally it could help facilitate a larger restructuring of local and regional transit into a centralised hub.

Locating a Hyperloop terminal in a downtown location could also have other wider reaching impacts beyond the immediate terminal site. A new transportation connection on the scale of Hyperloop would lead to an increase in foot traffic in the area surrounding the terminal location, which could be attractive to a range of business and retail sectors.

As such Hyperloop terminals could act as catalysts for intensification or regeneration of the surrounding areas. The potential development that a system like a Hyperloop passenger service could bring can be found in Vancouver, B.C. Metro Vancouver is interconnected by a regional rapid transit system consisting of automated light rail lines (known as the Skytrain), this higher order transit system has helped encourage economic growth around several of the station locations (see Exhibit 5).

Such intensification and growth are key signs of the positive impact strong transportation connections can bring to an existing urban core. Equally the stimulus impact on development from connecting very large metropolitan areas to neighbouring communities with very short travel times could also create regional centres of development and intensification by distributing the benefits of big market economies to areas in proximity to Hyperloop access points.

It remains to be seen if the Hyperloop can adopt many of the user-friendly transportation attributes of public transit with a very fast intercity transportation service.

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\(^{81}\) Higher Order Transit: Transit that generally operates in its own dedicated right-of-way, outside of mixed traffic, and therefore can achieve a frequency of service greater than mixed-traffic transit. Higher order transit can include heavy rail (such as subways), light rail (such as streetcars), and buses in dedicated rights-of-way.
There is growing discussion regarding the competition Hyperloop might create with short-haul flights. Unlike airports, Hyperloop terminals are expected to have the advantage of needing a much smaller footprint, thus increasing the number of locations where a terminal could be considered. Hyperloop would have the potential for location in an accessible part of the urban area close to major highways, rail, and other travel modes, possibly even in the heart of the downtown urban area, offering a high concentration of potential users and opening the service up to both business and recreational users who would have much quicker access to the system.

### 3.3.4 Security

At this stage, no regulation or guidance has been established to determine the security screening process for Hyperloop users. Approaches to security for existing modes such as air and rail differ significantly. Safety and security are highly complex, interdependent issues and are closely connected to perception and human emotion. Given the breadth of this issue, this section aims to lay out some key features informing the transportation industry’s approach to security in relation to modes such as rail and air travel.

Unlike air travel, Hyperloop will be constrained to fixed routes between large metropolitan areas. In many ways the Hyperloop mode, by design, is not overly dissimilar to high-speed rail (i.e. Eurostar) and/or MagLev rail in east Asia. Where conventional rail systems traverse topographies either at, above, or below grade, Hyperloop – as discussed earlier in this section – will travel in a tube that can also be above or below grade. In general terms the Hyperloop capsules/pods could be viewed as functionally similar to current rail carriages, albeit with the pressurized fuselage of a commercial airplane. It is this fundamental difference, coupled with other unresolved issues, that triggers questions and debate on the form of safety and the level security. A new mode like Hyperloop, travelling close to supersonic speeds, could be an attractive terrorist target.
The challenge facing both the Hyperloop companies and international government transport agencies is to strike a balance between a regulatory framework and legislation that will offer similar levels of security to current air and rail. Furthermore, how to reconcile this in today’s climate, where neither rail passengers, nor their luggage, are subject to security scans or screening.

In sharp contrast, given its low-pressure environment and ultra high speeds, there is concern that Hyperloop has the potential for, and may be susceptible to catastrophic accidents in the event of a major malfunction or malicious act.

There remains a significant amount of work to be done in understanding the possible impacts of a major failure in the system. Although the tube is expected to operate within a low-pressure environment, the details of that environment are still under refinement. The pressure levels within the tube will be an important factor in the scale of damage a major system failure (such as an explosion within the tube) could bring about. While it is envisaged that security procedures for both passengers and cargo will have some similarities to those of existing air and rail, as Hyperloop will be a high-profile service it may be considered appropriate to impose a more stringent form of screening during its initial deployment.

If eventually developed and deployed successfully, a Hyperloop system may be constructed across international borders. This would necessitate customs and immigration passenger screening and the production of travel documents such as passports. As the system is unlikely to be designed to allow for stopping at border crossings, any terminal which provides access to another country would require appropriate facilities to support a national border agency in undertaking their required screening duties.

In addition to terminals and capsules, the security of the tube and corridor will also be important. The engineering design section identified that the tube is expected to be constructed of steel and may be reinforced with concrete. This would not only provide the low-pressure environment but could also reduce the ability of external entities to cause damage to the tube. Monitoring the corridor by cameras and sensors is expected to be an important component of a network-wide security system, forming part of the operation control centre for the network. It is important to note that very little research into the unique security risks Hyperloop could create has been conducted at this stage, representing an area for significant further investigation.

3.4 Concept as a Freight Transportation Mode

Although the Hyperloop concept was originally conceived as a passenger mode of transportation in Musk’s Alpha paper, its potential application for freight was also acknowledged and has received greater interest as the technology has continued to develop. As a new mode of transportation, many uncertainties remain regarding the potential challenges of using the concept for freight, and significant testing is necessary to fully understand how the technology could be certified for freight transport use.

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\[82\] Musk, E. (2013). Hyperloop Alpha
There is growing interest in the use of Hyperloop for freight given that fewer challenges are anticipated in achieving operational readiness. If these short timescales for approval of freight are realised, a situation where the early adopters of Hyperloop use the route exclusively for freight is conceivable, providing an opportunity to deploy and operate the technology while any outstanding requirements for passenger transport are resolved. Although the freight market for Hyperloop is still in its infancy, several possible applications have been considered. However, limitations to the size, weight load and design of the pod are likely to impact the types of cargo that could be transported.

As well as size and capacity restrictions, traditionally freight demand is heavily influenced by cost, as well as factors such as transit time, regulatory requirements, and security considerations. As a result, there will likely only be a small number of freight types that would consider Hyperloop a viable mode for transport.

### 3.4.1 Pod Design

Currently, several different capsules/pods are being designed and developed by Hyperloop technology companies. These pods utilize different propulsion methods and as such, each has unique designs and capacities. As previously discussed, the internal design and layout of the pods have yet to be determined, with the current focus being on performance improvements. However, two different approaches to the handling of freight have been gaining interest from the technology companies.

The first approach considers the need for dedicated freight capsules. Designed specifically for freight, these would aim to maximize internal space for cargo storage. Several technology companies have acknowledged they are considering this approach and have even begun to consider ways to improve loading and unloading, with examples including the ability to open the capsule nose or to have bay doors on top of the capsule.

**Exhibit 6** shows a conceptual capsule configuration for freight transportation. A further consideration to this approach is the coupling together of multiple capsules. This has not been tested and as such remains a theory. However, if headways are sufficiently short, there might be no advantage to coupling multiple pods.

**Exhibit 6: Conceptual layout of a Hyperloop Capsule Configuration for Freight Transport**
The alternative approach is to have interchangeable units that could be loaded onto a capsule. Little information exists about these units, including how many a single capsule could hold. However, the concept would allow for units to be loaded in advance of capsule arrival, potentially reducing the amount of dwell time for a capsule at the loading point. The other advantage is that this allows for a single capsule to accommodate a mix of both passengers and cargo units.

There remain a large number of considerations to be addressed in order to progress the freight option. Although a few ideas have been presented, there has been no discussion yet regarding the sizing and design of Hyperloop transport containers. The currently developed tube diameters and pod designs would be unable to accommodate traditional road, rail, and sea cargo containers. As such, new containers would be needed, incurring additional cost and delays due to repacking on any trips involving multiple legs. Due to the lightweight design of the pods and the sensitivity in calibration for magnetic levitation, balancing the weight of any contents would also require careful loading and weight distribution which could also slow the loading process. Moreover, a significant number of freight sectors have additional requirements e.g. climate control or protective casing. How Hyperloop capsules might handle such requirements is still an unknown consideration at this stage.

3.4.2 Freight Infrastructure

Despite various viewpoints regarding how freight could be loaded and unloaded to/from the Hyperloop system, very little published material exists. Hyperloop companies have examined the concept of coupling pods together into freight consists, similar to rail freight, and have also discussed building designated freight handling facilities, but as yet no further discussions have taken place. Given the degree of uncertainty, it is difficult to identify what developments or designs have been considered for freight infrastructure, several factors however, can be noted.

The loading and unloading of capsules will need to be conducted in a manner that maintains the operations of the corridor. An operating model that involves a large number of capsules being loaded at any one time is unlikely given the anticipated cost of the capsules, as they will need to be kept in constant operation to maintain the level of service. As such, loading procedures will need to be streamlined to reduce capsule downtime resulting in freight facilities requiring sufficient space to store containers ready for immediate loading on arrival of a capsule. The land requirement for such activities could make this a difficult proposition for urban centres.

Given the speed at which the capsules will potentially travel, any freight would need to be well secured, likely involving similar practices to air freight with cargo containers designed to be easily strapped down. As previously noted, the containers will likely need to be custom designed, potentially compromising the compatibility of these containers with other transportation modes.
In addition to the uncertainty surrounding freight transportation, a lack of information exists regarding cargo distribution from a terminal. It is unlikely the terminal will be the final destination for the freight. Consideration should be given to whether loading facilities, mechanical winches, and cranes will be required at the terminal site. As well as tube-side infrastructure to support the loading and unloading of freight, facilities for connecting modes will also be required, which could include truck loading bays or intermodal facilities to transfer materials to rail.

Little information or available material on the operating procedures for Hyperloop freight exists at this stage. Loading requirements, onward connections, and other constraints could mean a downtown terminal location is unlikely to work well. Although still speculation at this stage, several technology companies have suggested that corridors will need to have both a downtown terminal for passengers and an edge of town terminal for freight.

3.4.3 Freight Competition

The travel speed Hyperloop claims to offer is likely to prove attractive to certain sectors of the freight industry. At present, water, air, rail, and road all provide freight services, with each offering certain benefits and advantages. Hyperloop, with its faster travel times but higher unit costs, will likely offer competition to modes that traditionally serve the urgent delivery sector (e.g. short shelf-life products or medical supplies/devices). As identified, there are likely to be many constraints on Hyperloop freight that will be significant in determining the types of services that use the system.

Given the uncertainties regarding capital and operational costs, see Section 5 – Estimates of Capital and Operating Costs, it is difficult to say what the costs will be, however, it is considered unlikely to be cost-effective for larger and non-time sensitive freight. Sending this sort of freight to a downtown terminal presents several challenges, such as higher storage costs due to the higher land values, more complexity in moving the freight from the downtown location to the final destination, potential restrictions on the hours of operation, etc. Conversely, an edge of town Hyperloop terminal could create a scenario where the system becomes more cost-competitive with road transportation and the expectation that the system could be in operation 24 hours a day would also give an advantage. Another benefit is that the pods do not require a driver, something the competing modes do require; this could significantly reduce costs as well as remove the human safety limitations that industries such as road and rail have to comply with.

Hyperloop is not only forecast to provide competition for existing freight modes, it is also being considered as a complementary mode that could alleviate existing capacity issues. In North America there is a significant shortage of truck drivers, while air traffic continues to grow causing growing environmental concerns. Hyperloop could potentially provide the additional capacity needed to relieve pressure on the road haulage industry, while also helping reduce wear and tear on the road network. Equally, the suggested zero-emissions of Hyperloop (based on present designs and estimates) could help tackle the environmental concerns that more diesel trucks, locomotive engines, and short-haul flights create.
The speed at which the system is anticipated to travel could also make it more attractive than existing modes in some instances, thereby not only alleviating the freight short-haul, but generating modal shift to a ‘greener’ mode. It should be noted that although the mode could be considered ‘greener’ than other modes, for many of the freight movements Hyperloop will only represent part of the journey. First and Last mile journeys will likely be required for most of the goods being moved by Hyperloop, which will somewhat diminish the benefits, particularly if some of the freight movements are induced demand.

Along with the impact of Hyperloop on existing modes, it is also expected to have an added effect on economic activities along the corridors where it is implemented. The creation of new high-speed connections could encourage new growth in knowledge-driven industries, which might choose to locate around accessible nodes of the alignment due to the increased accessibility to their customers/suppliers and highly skilled workforces that such a system might provide. These corridors and stations would have significant economic implications for land use patterns and could act as a catalyst for the regeneration of current brown-field sites. The new connections would not only provide locations for new businesses and economic activity, they could also open new markets and provide access to new workforces.

Although opinions differ, many technology companies expect that the terminal locations for passenger transportation are likely to be in a downtown location. This would impact traditional freight opportunities, with only freight intended for locations in close proximity to the downtown terminal finding this location beneficial. This could mean that, as well as urgent deliveries, there may also be opportunity for some non-time sensitive freight to use the Hyperloop system, based on the premise proposed by several of the Hyperloop companies that the cost per ton for freight shipping would be lower than alternative modes to these downtown locations. Equally, sharing space on passenger pods and utilizing pods not at full passenger capacity could further reduce freight costs.

Although there are a number of freight opportunities for Hyperloop, it’s unlikely the system would be considered appropriate for all freight. Capsule size will significantly limit the types of freight to be transported, with most systems operating capsules with a diameter not much greater than 4m. Rail and roads currently transport a range of large freight items unlikely to fit inside a Hyperloop capsule. Equally, the issues of acceleration and deceleration at the rates currently being discussed present a problem for some freight. As discussed in Section 3 – Hyperloop Concept and Engineering Design, the pods are capable of extreme acceleration and deceleration. Without human occupants, it is feasible for the pod to accelerate and brake at much higher G-Forces, further reducing travel times. Additional studies would be needed to understand the impact such operating parameters could have on various freight types.

To date (March 2020), very limited testing and consideration has been given to the possible applications of Hyperloop in the wider freight sector. Due to its high price-sensitivity it is difficult, at this stage, to effectively assess if any traditional freight types will see a competitive advantage in using Hyperloop. In addition to the unclear cost, any potential legislative or regulatory requirements have yet to be established for Hyperloop. Until greater clarity can be provided over cost, design, and regulations it is not possible to assess the specific market application for Hyperloop freight.
4. Regulatory Regime for Hyperloop

4.1 Introduction

To date (March 2020), Hyperloop technology developers have proceeded to develop their concepts on the general premise of a high-speed, ground-based approach involving propulsion systems and operating environments that have not been commercially achieved before in North America and have no common-carriage regulatory precedent. As such, an essential step in determining the feasibility of any Hyperloop concept is to understand the potential risks and safety hazards associated with how such a system could operate. Developing a list of hazards and threats will help identify where mitigation measures might be required. Mitigation measures can take many forms ranging from informal guidance or direction, through to legislation and regulations that can be enforced, and non-compliance penalized.

With Hyperloop technology still in the early stages of development and testing, a significant number of factors (e.g. how high-speed switching will work) remain unknown. This means that changes to the hazards and threats are expected as the technology continues to evolve towards implementation. This section provides a high level, initial review of possible threats and safety concerns. Significant further studies will be required to better understand the changing risks as the technology develops.

The section is structured in three main areas:

The *first* part presents a preliminary hazard/threat/vulnerability assessment to identify current risks potentially requiring mitigation measures. In instances where the technology requires further development or understanding, the risks identified could change as the design is refined and greater clarity over the final operating parameters of the component are established. Equally, they could provide support for the value of proactive regulations or guidance in helping shape and guide technology development.

The *second* section classifies the various hazards and threats into policy areas and begins the process of establishing where guidance, governance, and any other oversight might come from and what mitigation measures could look like. Although Hyperloop is a new technology, elements of the system may be closely aligned with measures used by other transportation modes. However, there will also be gaps and questions around some aspects that the process will raise.

In the *third* and final section the various areas for consideration are discussed, expanding on some of the component complexities and challenges with examples of how other transportation modes have tackled similar challenges. The various approaches being taken by other international organizations and agencies to address the concerns Hyperloop presents are also discussed, including standardization of the system parameters to avoid cross-border issues.
4.2 Preliminary Hazard and Threat & Vulnerability Assessment

The Preliminary Hazard Assessment is a basic inductive analysis technique developed to identify safety hazards using a “top-down” approach (e.g., define the system, define the hazards/threats/vulnerabilities, then recommend resolutions for the hazards/threats/vulnerabilities) to determine the effects of a system event or system malfunction. The Preliminary Hazard Assessment format provides an organized, systematic framework to follow in presenting potential hazards/threats/vulnerabilities, causes, recommendations, and control measures. Furthermore, it offers the opportunity to consider and discuss potential hazards and vulnerabilities the technology could present. This step is important because historical data and past experience do not necessarily reflect all potential safety hazards and their effects.

Safety and security are core components of Transport Canada’s legislative and regulatory frameworks. To understand some of the safety considerations that a new technology like Hyperloop might raise, a series of assessments of the various components and scenarios were conducted. AECOM undertook two assessments, a Preliminary Hazard Assessment (PHA) and a Threats and Vulnerabilities Assessment (TVA), to identify potential hazards, threats, and vulnerabilities.

It is important to acknowledge, at this stage, that the assessments have been conducted using data available in the public domain, information provided by Hyperloop technology companies, and insight provided by industry experts. However, as the technology is still in its infancy and continues to evolve on an almost daily basis, these assessments will only serve as an initial review of the risks and will require further review as the technology comes closer to actualization.

4.2.1 Assessment Methodology

The assessments are based on a phased approach where risks are first identified, then evaluated for severity and impact, before recommendations to assist in eliminating, mitigating, or controlling hazards are discussed. Hazards commonly considered in this assessment process are typically those that could potentially cause:

- Loss of life and/or serious injury to users and personnel.
- Serious damage to facilities and/or equipment resulting in large financial loss.
- Failures with serious adverse impact on system capability, system operability, the environment, or public perception.

The methodology utilized for identifying hazards associated with the Hyperloop system consists of the following analytical steps:

- Define the physical and functional characteristics of the system, and any operations to be performed and followed.
- Identify hazards that may be present during the system lifecycle and determine the contributing factors of each.
- Assess the hazards to determine severity and probability, and to recommend means for their elimination, mitigation or control.

Hazard severity categories, as summarized in Table 12, define the impact of the occurrence as it relates to users and personnel error, environmental conditions, design inadequacies, procedural deficiencies, or system/component failure or malfunction. The severity is scored on a scale of 1 to 4 and colour coded respectively based on the level of impact for ease of communication.

**Table 12: Severity Categories**

<table>
<thead>
<tr>
<th>Severity Category</th>
<th>Description</th>
<th>Result Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Catastrophic</strong></td>
<td>Operating conditions are such that human error, environment, design deficiencies, element, subsystem or component failure, or procedural deficiencies may cause death or major system loss, thereby requiring immediate cessation of the unsafe activity or operation.</td>
</tr>
<tr>
<td>2</td>
<td><strong>Critical</strong></td>
<td>Operating conditions are such that human error, environment, design deficiencies, element, subsystem or component failure or procedural deficiencies may cause severe injury or illness or major system damage thereby requiring immediate corrective action.</td>
</tr>
<tr>
<td>3</td>
<td><strong>Marginal</strong></td>
<td>Operating conditions may commonly cause minor injury or illness or minor systems damage such that human error, environment, design deficiencies, subsystem or component failure or procedural deficiencies can be counteracted or controlled without severe injury, illness or major system damage.</td>
</tr>
<tr>
<td>4</td>
<td><strong>Negligible</strong></td>
<td>Operating conditions are such that personnel error, environment, design deficiencies, subsystem or component failure or procedural deficiencies will result in no, or less than minor, illness, injury or system damage.</td>
</tr>
</tbody>
</table>

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As well as the severity of an occurrence, the probability of such a hazard also needs to be considered and categorized. The probability of an occurrence is assigned a letter from A to E based on the likelihood of the event and is described in Table 13.

Table 13: Probability Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Definition (Specific Individual Item)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Frequent</td>
<td>Likely to occur often in the life of an item.</td>
</tr>
<tr>
<td>B</td>
<td>Probable</td>
<td>Will occur several times in the life of an item.</td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
<td>Likely to occur sometime in the life of an item.</td>
</tr>
<tr>
<td>D</td>
<td>Remote</td>
<td>Unlikely, but possible occurrence in the life of an item.</td>
</tr>
<tr>
<td>E</td>
<td>Improbable</td>
<td>So unlikely it can be assumed occurrence may not be experienced.</td>
</tr>
</tbody>
</table>

Building upon both the hazard category and frequency of occurrence as defined in Tables 12 and 13, a Hazard Risk Index (HRI) is determined considering both the severity and the probability of a hazard, as summarized in Tables 14 and 15. The two assessment systems (PHA and TVA) utilize this rating guide approach.

Table 14: Preliminary Hazard Assessment and Threats and Vulnerabilities Assessment (Rating Guide)

<table>
<thead>
<tr>
<th>Frequency of Occurrence</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Frequent</td>
<td>IA</td>
<td>IIA</td>
<td>IIIA</td>
<td>IVA</td>
</tr>
<tr>
<td>(B) Probable</td>
<td>IB</td>
<td>IIB</td>
<td>IIIB</td>
<td>IVB</td>
</tr>
<tr>
<td>(C) Occasional</td>
<td>IC</td>
<td>IIC</td>
<td>IIIC</td>
<td>IVC</td>
</tr>
<tr>
<td>(D) Remote</td>
<td>ID</td>
<td>IID</td>
<td>IIID</td>
<td>IVD</td>
</tr>
<tr>
<td>(E) Improbable</td>
<td>IE</td>
<td>IIE</td>
<td>IIIE</td>
<td>IVE</td>
</tr>
</tbody>
</table>

The Hazard Risk Index (HRI) score assists decision-makers in determining whether hazards should be eliminated, mitigated, controlled, or accepted. The action to be taken will depend on the score, although it should be noted that in all situations the ideal solution is to eliminate the risk irrespective of the score. Where elimination is not feasible, the probability or severity of the event can be mitigated by design modifications or by incorporating safety devices, warning devices, or procedures, thereby reducing the HRI score.\(^6\)

Once the various hazards and threats have been scored, Table 15 identifies suggested actions. As an example, a hazard risk of IIB is assigned an HRI score of 1, which suggests that it is an unacceptable threat and that corrective action must be taken.

**Table 15: Hazard Risk Index (HRI) Score**

<table>
<thead>
<tr>
<th>Hazard Risk Index</th>
<th>HRI</th>
<th>Suggested Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA, IB, IC, II A, IIB, IIIA</td>
<td>1</td>
<td><strong>Unacceptable</strong> (An intolerable risk that must be reduced)</td>
</tr>
<tr>
<td>ID, IIC, IID, IIB, IIIC</td>
<td>2</td>
<td><strong>Undesirable</strong> (Reduce the risk until further risk reduction is grossly disproportionate. Residual risk must be quantitative or semi-quantitatively assessed and well understood)</td>
</tr>
<tr>
<td>IE, IIE, IIID, IIIE, IVA, IVB</td>
<td>3</td>
<td><strong>Acceptable with Corrective Action</strong> (Reduce risk until further risk reduction costs exceed the benefit gained. The residual risk may be more subjectively assessed)</td>
</tr>
<tr>
<td>IVC, IVD, IVE</td>
<td>4</td>
<td><strong>Acceptable without Corrective Action</strong> (Broadly acceptable with periodic review. Application of existing best practices where available is deemed to reduce risk to this level)</td>
</tr>
</tbody>
</table>

### 4.2.2 Preliminary Hazard Assessment (PHA)

The Preliminary Hazard Assessment for Hyperloop was conducted by first reviewing and identifying the various components or areas of the system that could present hazards. Selection of these areas was based on the findings from Section 2 - Literature Review, input from Hyperloop technology companies, and expert insight to identify components of the system that raised potential threats or hazards. Although it is possible to foresee potential hazards for the components already developed or being tested, understanding those for elements that are not yet developed is more challenging. To provide greater clarity on what these might be, the assessment considered the findings and direction provided in Section 3 – Hyperloop Concept and Engineering Design.

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The review considered various infrastructure-based components and potential hazards, as well as soft systems and procedures, and generated the following focus areas for review:

<table>
<thead>
<tr>
<th>I</th>
<th>Vehicles (Hyperloop Capsules/Pods)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Power Systems</td>
</tr>
<tr>
<td>III</td>
<td>Transport Corridor and Tube Infrastructure</td>
</tr>
<tr>
<td>IV</td>
<td>Communications</td>
</tr>
<tr>
<td>V</td>
<td>Terminals</td>
</tr>
<tr>
<td>VI</td>
<td>Vehicle Staging and Maintenance Facilities</td>
</tr>
<tr>
<td>VII</td>
<td>Operations and Maintenance</td>
</tr>
</tbody>
</table>

(I) Vehicles (Hyperloop Capsules/Pods)

A core component of the Hyperloop system is the vehicle (pod/capsule) that will be used to transport people and/or goods. An essential feature of the system is the low-pressure operating environment. This requires pressurization of the capsule interior for the safety and comfort of users, which creates several potential hazards relating to the pressure differences in the system. Equally important, and another consideration for the capsules, is the ability to enter and exit the pods, whether at a planned stop or in the event of an emergency. This could be particularly important given that the pod will have a limited onboard air supply. Table 16 provides an assessment of the identified potential vehicle-related hazards.

Table 16: PHA – Vehicles (Hyperloop Capsules/Pods)

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Hazard Risk Index</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>A drop in cabin pressure due to a pressure leak in the exterior of the vehicle.</td>
<td>There is a wide range of possible causes, including collision with tube infrastructure, corrosion or deterioration of the vehicle, and intentional damage to the vehicle.</td>
<td>IIIC</td>
<td>That the vehicle design includes the provision of redundancies in the event of physical contact/collision with the exterior and that a monitoring and maintenance regime is established.</td>
</tr>
<tr>
<td>02</td>
<td>Pressure imbalance created by failure of vehicle door to seal properly.</td>
<td>Deterioration of the vehicle door seal</td>
<td>IIIC</td>
<td>Recommend the vehicle door be designed with redundancy factors and ensure regular pod maintenance and monitoring.</td>
</tr>
<tr>
<td>Hazard Number</td>
<td>Hazard Description</td>
<td>Cause</td>
<td>Hazard Risk Index</td>
<td>Recommendations</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>03</td>
<td>Vehicle collision with track or magnets&lt;sup&gt;87&lt;/sup&gt;.</td>
<td>Misalignment of the magnetic or air cushion system used for levitation and guidance</td>
<td>ID</td>
<td>Ensure a regular track and pod monitoring and maintenance program is in place</td>
</tr>
<tr>
<td>04</td>
<td>Technical failure of the life support system.</td>
<td>An internal system failure that compromises the life support system</td>
<td>ID</td>
<td>An in-pod backup system should be provided</td>
</tr>
<tr>
<td>05</td>
<td>Pod door unable to open or close in the tube.</td>
<td>Mechanical door failure in an emergency</td>
<td>IVD</td>
<td>Regular maintenance of the doors should be conducted, and an alternative escape hatch included in the vehicle design</td>
</tr>
<tr>
<td>06</td>
<td>Pod door unable to open or close at a station.</td>
<td>Mechanical or software door failure at a scheduled stop</td>
<td>IVC</td>
<td>Regular maintenance and monitoring of the doors and the subsystems</td>
</tr>
<tr>
<td>07</td>
<td>Where utilised, low-speed wheels do not retract/deploy.</td>
<td>A failure of the wheels through either mechanical or electrical faults</td>
<td>IIID</td>
<td>Ensure regular wheel maintenance and monitoring</td>
</tr>
</tbody>
</table>

The Preliminary Hazard Assessment of possible hazards related to the vehicles resulted in the identification of a series of risks that could arise from a lack of monitoring and maintenance (e.g. similar to those affecting the maintenance of aircraft fuselages).

<sup>87</sup> Shanghai Maglev Train / Transrapid (China), SCMaglev (Japan)
To address and reduce the chance of these risks, it is suggested that requirements regarding the monitoring and maintenance of the pod are developed. Additionally, several pod design features, including reserve air systems and emergency exits, should also be considered.

(II) **Power Systems**

All of the consulted Hyperloop technology companies agree that Hyperloop will operate on electric power; whether this is supplied from internal batteries or the infrastructure side is where approaches differ.

As the primary means of propulsion, life support, communications, and operations, the need for the power source to be reliable and provide a steady energy flow are both important factors. **Table 17** shows a range of power-related hazards, including potential causes and recommendations.

**Table 17: PHA – Power Systems**

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>08</td>
<td>Power to the entire system is cut.</td>
<td>An area-wide or system-wide power outage</td>
<td>IIIIB</td>
<td>Internally powered pods: Safety procedures for operating without infrastructure side power will need to be developed. Infrastructure side powered pods: Development of a redundant system within the pods that allows them to reach safe evacuation areas.</td>
</tr>
<tr>
<td>09</td>
<td>Temporary spike or drop in energy supply.</td>
<td>A surge in the power system</td>
<td>IVA</td>
<td>Ensure pods and infrastructure are designed with surge protection measures</td>
</tr>
<tr>
<td>10</td>
<td>The magnet gap between the primary and secondary motors fluctuates during operation, creating varying air gaps(^8).</td>
<td>The energy supply to the motors is not steady</td>
<td>IIA</td>
<td>Careful monitoring and design requirements for the supply of power to the motors will be required to reduce the impact</td>
</tr>
</tbody>
</table>

---

The results of the Preliminary Hazard Assessment related to power systems suggest there are several questions relating to the provision of redundancy power systems that need additional consideration.

Equally, further exploration of how the system and the magnetic propulsion and levitation systems would handle a complete power outage during operations could provide insight into possible Hyperloop regulatory requirements.

(III) Transport Corridor and Tube Infrastructure

The infrastructure and corridor for Hyperloop will pose a series of challenges and potential hazards both during the construction and operation of the route. Key among these is how the tube and magnetic track (if used) are impacted by any changes to environmental conditions (e.g. Musk notes the importance of the ability of the infrastructure to withstand natural disasters). Along with the Hyperloop infrastructure, the corridor itself presents potential risks such as vegetation incursion and the impact of neighbouring development. Potential hazards, their causes and recommendations for the Hyperloop right-of-way are presented in Table 18.

Table 18: PHA – Corridor and Tube Infrastructure

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>External air enters the tube, reducing the low-pressure environment.</td>
<td>Leak in tube pressure as a result of tube puncture, damage or corrosion of seals or materials</td>
<td>IVC (The tube is unlikely to remain airtight. However, the impact of a leak would be small)</td>
<td>Design the tube and seals with safety factors where possible and ensure regular tube maintenance and monitoring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Tube deformation(^9)</td>
<td>Environmental conditions, aging of infrastructure and excessive loads could all generate tube deformation</td>
<td>ID</td>
<td>Where feasible, design the tube with safety factors and ensure regular tube maintenance and monitoring</td>
</tr>
<tr>
<td>15</td>
<td>Structural deformation of pylons</td>
<td>Environmental impacts, vegetation growth, and soil settlement could all compromise structural integrity</td>
<td>IID</td>
<td>Design the structures with additional capacity and conduct regular monitoring and maintenance</td>
</tr>
<tr>
<td>16</td>
<td>Vacuum pump failure(^9)</td>
<td>The deterioration of a vacuum pump</td>
<td>IVC</td>
<td>Design the system with redundant pumps and ensure regular pump maintenance and monitoring</td>
</tr>
<tr>
<td>17</td>
<td>Damage to the electrical systems</td>
<td>Lightning</td>
<td>IIIC</td>
<td>Install lightning rods</td>
</tr>
<tr>
<td>18</td>
<td>Trees falling on the tube</td>
<td>Storms or other adverse weather conditions</td>
<td>IIID</td>
<td>Ensure regular removal of vegetation and trees from the corridor</td>
</tr>
<tr>
<td>19</td>
<td>Surounding infrastructure or debris falling on the tube</td>
<td>Storms or other adverse weather conditions</td>
<td>IIID</td>
<td>Careful consideration and planning of any neighbouring land use should be factored into the planning process for a Hyperloop system</td>
</tr>
<tr>
<td>20</td>
<td>High-Speed Switch failure</td>
<td>Technical failure of a component in the switch mechanism that prevents operation</td>
<td>IIIC</td>
<td>A process for monitoring and maintenance of switches should be established to minimize operational issues</td>
</tr>
</tbody>
</table>

\(^9\) Hyperloop Technologies, ‘Low-Pressure Environment Structures’, USA, January 2016
\(^9\) Virgin Hyperloop One, HyperloopTT, Hardt
The Preliminary Hazard Assessment for the Hyperloop corridor and tube infrastructure has identified that a series of processes for the monitoring and maintenance of the infrastructure will be required. It also highlighted the importance of the design process and sound infrastructure construction and suggests some factors relating to neighbouring land uses and environmental elements that will require consideration during the design and operation of the corridor.

(IV) Communications

Hyperloop technology companies have identified that effective communication procedures and protocols will be critical to safely coordinate the small headways the system is expected to operate under. The potential hazards posed by a partial or entire system failure were considered and several possible hazards have been identified in Table 19 along with possible causes and potential recommendations to reduce the likelihood or impact of these hazards.

Table 19: PHA – Communications

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Loss of data connection rendering pod location unknown92</td>
<td>Location communications system failure</td>
<td>IIB (It is anticipated that interruptions to communications will be a regular occurrence; without mitigation this could be a serious risk)</td>
<td>A series of redundant communication systems be put in place and operating procedures developed for these scenarios</td>
</tr>
<tr>
<td>22</td>
<td>Vehicle brakes too early (stopping before exiting the tube)</td>
<td>Communications failure between system and pod</td>
<td>IIC (Communications are susceptible to failures; without appropriate backups the consequences could be significant)</td>
<td>Design a secondary communication system that can confirm and monitor pod speeds and headways</td>
</tr>
<tr>
<td>23</td>
<td>Vehicle brakes too late (overshooting a station or tube exit)</td>
<td>Communications failure between system and pod</td>
<td>IC (Although unlikely to occur due to relative simplicity of the system, if it did the consequences could be severe)</td>
<td>Design a secondary communication system that can confirm and monitor pod speeds and headways. Install/need for a secondary emergency braking system</td>
</tr>
</tbody>
</table>

The Preliminary Hazard Assessment for Hyperloop communications has highlighted the importance of these systems for maintaining safety, especially given the extreme travel speeds. To mitigate these risks the recommendations, include the development of a series of operating procedures for various scenarios. The recommendations also identify the need for redundant communication systems to provide contingency options.

(V) Terminals

The design concept of the Hyperloop terminal is not yet well known, with very little public material available describing how it might look and operate. This makes undertaking a hazard assessment difficult. There are, however, a number of shared elements in a transit terminal and these form the basis of this assessment. Potential hazards relating to Hyperloop terminals are discussed in Table 20.

Table 20: PHA – Terminals

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Damage/failure of pod boarding/aligning equipment</td>
<td>Damage could result from human error or faulty equipment</td>
<td>IID</td>
<td>Develop and enforce maintenance protocols and regular monitoring of infrastructure and equipment</td>
</tr>
<tr>
<td>26</td>
<td>Occupational and user error hazards</td>
<td>Not following procedures or equipment failure</td>
<td>IID</td>
<td>Develop and enforce procedures for staff and passenger management during critical processes</td>
</tr>
</tbody>
</table>
With such limited information regarding how the terminals might operate, the Preliminary Hazard Assessment has identified the importance of suitable procedures for the safe management of staff and passengers alike. Equally, the terminals will need to have suitable processes and redundancies to ensure that pods arrive and leave the terminal building in a safe manner.

(6) Vehicle Staging and Maintenance Facilities

There is still very little information regarding the design, requirement for, and possible approach to Hyperloop vehicle maintenance and storage facilities. However, there are a couple of common risks that any transportation storage or maintenance facility should consider; these include damage to vehicles and personnel as well as theft and vandalism of equipment. Several potential hazards pertaining to storage and maintenance of Hyperloop vehicles are presented in Table 21.

Table 21: PHA – Vehicle Staging and Maintenance Facilities

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Terminal pod exit/entry system failure</td>
<td>Technical failure of components/system that loads/unloads pods for travel</td>
<td></td>
<td>Ensure the monitoring process of the mechanisms and that suitable redundancies are available</td>
</tr>
<tr>
<td>28</td>
<td>Damage to vehicles during storage or maintenance</td>
<td>Damage could result from human error or faulty equipment</td>
<td>IID</td>
<td>Develop and enforce maintenance protocols and regular monitoring of infrastructure and equipment</td>
</tr>
<tr>
<td>29</td>
<td>Occupational Hazard</td>
<td>Not following procedures or equipment failure</td>
<td>IID</td>
<td>Develop and enforce maintenance protocols and regular monitoring of infrastructure and equipment</td>
</tr>
<tr>
<td>30</td>
<td>Theft or vandalism of equipment at maintenance and/or storage yards</td>
<td>Theft by staff or trespassing by unauthorized individuals</td>
<td>IID</td>
<td>Ensure maintenance yards are secured, and that staff are appropriately vetted and monitored</td>
</tr>
</tbody>
</table>
The Preliminary Hazard Assessment for maintenance yards, facilities, and vehicle staging has identified a few possible risks. However, with limited information regarding these facilities and their operation, further hazards will likely be identified as more details are developed. The assessment does identify the need for maintenance procedures to be developed and followed, which will form an important part of the system operation.

(VII) Operations and Maintenance

Hyperloop technology companies have talked about the development of complex networks of Hyperloop corridors and routes that could involve multiple connections and switches. The operation of such a system would require careful monitoring and procedural processes. The assessment of potential hazards and vulnerabilities associated with Hyperloop operations and maintenance included identifying various operational issues, from non-functioning equipment to network operations issues such as trespassers and blocked tubes. Table 22 details several possible hazards.

Table 22: PHA – Operations and Maintenance

<table>
<thead>
<tr>
<th>Hazard Number</th>
<th>Hazard Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>Full or partial failure of network monitoring equipment</td>
<td>System failure could result from power outages, IT issues, or communication issues</td>
<td>IIC</td>
<td>Develop redundancies for network management and operational systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(The likelihood of the network system being unavailable is small, although the impact on operations would be critical)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Collision with an object in the tube</td>
<td>Humans may trespass into the tube, or material may have been left by previous pods</td>
<td>IE</td>
<td>Ensure that access to tubes is secured and that monitoring is in place</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Given the speed of travel any impact has the potential to be catastrophic. The event probability is considered improbable)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Pod stalled/ stopped at station</td>
<td>Possible causes include a medical emergency, equipment failure, or security concerns</td>
<td>IVB</td>
<td>Consider station designs that allow for stationary pods without impacting operational performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(It is anticipated that pods will be stopped at stations on occasion; the impact is considered negligible)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Pod stalled/ stopped in tube</td>
<td>Possible causes include a medical emergency, equipment failure, or security concerns</td>
<td>IID</td>
<td>Develop a series of procedures for the management of various unplanned situations during pod operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(It is considered unlikely that a pod would stop in the tube in these situations, although doing so would present a critical risk)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Preliminary Hazard Assessment for Hyperloop operations and maintenance has identified several possible risks that could impact the network. To mitigate these risks, a series of network management redundancy systems will be needed, along with network security and monitoring systems. As well as the hardware requirements, it is recommended that a series of procedural processes be established to provide a protocol for a range of possible events.

4.2.3 Threat and Vulnerability Assessment (TVA)

The Threat and Vulnerability Assessment (TVA) is a tool used to identify possible security vulnerabilities, their causes, potential control measures, and the assignment of an associated risk level. An assessment was performed on the Hyperloop technology to identify potential risks relating to Security and Emergency Management. The following hazards and vulnerabilities were identified through a review of the concept (as of March 2020), including reviewing the Hyperloop Concept and Engineering in Section 3 and where available, input gathered from the various Hyperloop technology developers. The hazards and vulnerabilities assessed in the TVA include:

<table>
<thead>
<tr>
<th></th>
<th>Emergency evacuation during terrorism-related incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>On-board passenger-related incidents</td>
</tr>
<tr>
<td>III</td>
<td>Emergency evacuation during extreme natural events</td>
</tr>
<tr>
<td>IV</td>
<td>Fire or water in the tube/pod</td>
</tr>
<tr>
<td>V</td>
<td>Oxygen leak / no oxygen in the pod</td>
</tr>
<tr>
<td>VI</td>
<td>Trespassing in the tube or corridor</td>
</tr>
</tbody>
</table>

Table 23 provides an overview of the threats and assesses the possible risks. Further discussion on each hazard is provided below.

Table 23: TVA for Hyperloop System

<table>
<thead>
<tr>
<th>Threat Number</th>
<th>Threat Description</th>
<th>Cause</th>
<th>Risk Assessment</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Emergency evacuation during terrorism-related incidents</td>
<td>An act of terrorism is either threatened or occurs within the Hyperloop system</td>
<td>IE</td>
<td>Introduce protocols to reduce the vulnerability of the system including, pre-screening, monitoring systems, and working with enforcement agencies</td>
</tr>
<tr>
<td>02</td>
<td>On-board passenger-related incidents</td>
<td>A medical emergency, security threats or user</td>
<td>IIIIC</td>
<td>Design appropriate emergency evacuation</td>
</tr>
<tr>
<td>Threat Number</td>
<td>Threat Description</td>
<td>Cause</td>
<td>Risk Assessment</td>
<td>Recommendations</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>03</td>
<td>Emergency evacuation required during extreme natural events</td>
<td>Various natural disasters such as earthquakes, floods, and storms</td>
<td>(Although steps can be taken to reduce the chance of such events, they are not fool proof. In the event such an issue occurs, the impact can be reduced)</td>
<td>points, carry medical equipment, and develop monitoring of users that could present a risk to the system</td>
</tr>
<tr>
<td>04</td>
<td>Fire in the capsule/pod</td>
<td>Various technical malfunctions such as short-circuiting of power supply system or friction points creating sparks</td>
<td>(Natural events do occur and should be planned for; their impacts are likely varied)</td>
<td>Design emergency evacuation points and implement a monitoring system for such events. Elevated vs below grade infrastructure become important design considerations</td>
</tr>
<tr>
<td>05</td>
<td>Oxygen leak / no oxygen in the pod</td>
<td>Failure of the onboard oxygen system</td>
<td>(Severity would be determined by how little oxygen was provided. Such an event is considered unlikely given the design and robustness of the systems)</td>
<td>Ensure a backup system is included in all pods, and that regular system maintenance is conducted</td>
</tr>
<tr>
<td>06</td>
<td>Trespassing in the tube or corridor</td>
<td>Trespassers access the tube network through access/egress points. Trespassers access ancillary facilities such as pumping stations or maintenance yards</td>
<td>(Given the interest in the system it is likely that people will try to gain access. The severity could be high if they gain access to the tube)</td>
<td>Ensure that appropriate inspections of tube access and egress points are conducted as well as monitoring of ancillary facilities</td>
</tr>
<tr>
<td>07</td>
<td>Communications system is compromised</td>
<td>External or internal unauthorized access to communications systems and protocols. (e.g. Cyber-terrorism)</td>
<td>(A growing concern of many infrastructure systems. In the event of successful access, the impacts could be catastrophic)</td>
<td>Suitable system security measures are implemented, and monitoring conducted</td>
</tr>
</tbody>
</table>
(I) **Emergency Evacuation during Terrorism-related Incidents**

As a high-profile transportation system, there are concerns that Hyperloop could be a potential target for terrorist attacks. Various elements of the system could be targeted, including the vehicles, the tube, the terminals, and the network operations. There are two main components to consider when assessing this threat: firstly, how to prevent such an incident, and secondly, how to react in the event of an incident occurring.

The prevention of a terrorist act against the Hyperloop system involves a range of factors, many of them are beyond the control of the Hyperloop operators (e.g. police agencies).

However, there are still several measures operators can consider. Similar to existing aviation procedures, these include pre-screening of passengers, security scans of freight and cargo, and security monitoring of the corridor.

In the event of a terrorist act, the primary focus will be on emergency evacuation of the system. Procedures for the evacuation of terminals and facilities in such events should be established based on existing best practices and governance (e.g. airports or rail terminals, which are likely to be the closest current comparisons).

The safe evacuation of pods in the tube represents a new area. One suggestion from the Delft Institute is the development of safe havens along the corridor, designed and located based on an acceptable evacuation time for passengers. The location of a safe haven must also allow ease of access for emergency service providers. This system would provide predetermined locations for evacuation, allowing for improved coordination between emergency responses and system operators.

(II) **On-board Passenger-Related Incidents**

There are a number of possible on-board passenger incidents that could occur, such as a medical emergency, a security threat, or user-generated mechanical failure.

The development of procedures regarding the handling of such events will be important in ensuring that the rate and severity of such instances does not increase. The system should be designed with emergency access points (potentially the safe haven concept), to allow for external assistance, as well as the capacity for evacuation.

Pod interiors should be designed to include First Aid kits, an AED machine, and an emergency response call/communication system. Passenger screening might be required and advice on how travel could affect pre-existing medical conditions should be provided.

Operational procedures will determine whether an event requires an emergency stop or if (e.g. for medical emergencies) it is more appropriate to continue to the next station where assistance can be provided.
(III) Emergency Evacuation during Extreme Natural Event(s)

In the case of an extreme natural event, network operations will need to implement a shutdown of the affected area and, if appropriate, an emergency evacuation of the tube. This will require an operation-centre based warning system to advise of potential natural events and established operating procedures for how to deal with various scenarios.

(IV) Fire in the Capsule / Pod

A fire within the capsule/pod could result from the short-circuiting of the Hyperloop’s power supply system or friction between two points, creating sparks. Such an incident requires both fire-suppression measures, such as fire-resistant materials and fire-management to contain and/or minimize the event, as well as evacuation measures.

The implementation and enforcement of monitoring and maintenance protocols should also reduce the risk of such an event occurring.

(V) Oxygen Leak / No Oxygen in the Pod

As the pods will operate in a low-pressure environment, passengers will require oxygen within the pod. In the event of an oxygen-system or tank failure the pod could be left with reduced or potentially no oxygen. To mitigate or control such an event, oxygen tanks should be designed with a safety factor and include redundant oxygen tanks and oxygen masks within the Hyperloop pod.

A regular maintenance program for the system should also be conducted to ensure sufficient supply and reserves are available for each trip.

(VI) Trespassing in the Tube or Corridor

Although the entrances and exits for the tube and pods are expected to be secured there still exists a risk of trespass within the system (e.g. utilizing one of the emergency access points). Equally, trespassing onto the tube corridor could raise concerns regarding operational safety and system security. Regular inspections of all access and egress points along the system will be extremely important, with measures put in place and reviewed regularly to prevent unauthorized access.

Consideration should be given to security of other infrastructure such as the pylons, terminals, pumping stations, and maintenance facilities to prevent unwanted access.
4.3 Key Groupings

After assessing the potential hazards and threats of the Hyperloop technology as outlined in Section 4.2, it was possible to group most of these risks into a number of key areas.

These six areas act as high-level groupings for the various risks. Although individually identified, safety as a policy area is inherent in each of the six groupings and so has not been separated.

4.3.1 Policy Association

The areas listed aim to capture and categorize the risks identified through the Preliminary Hazard and Threat and Vulnerability Assessments. Identified risks that do not fall under one of these main groupings are discussed further in Section 4.4.

Vehicle Design

- Hazards and Threats covered: H01, H02, H03, H04, H05, H06, H07, H08, H09, H10, H11, H22, H23, H28, H33, H34, T04 and T05

The capsule or pod is at the centre of each technology company’s design and represents many of the innovative technological elements of the Hyperloop system. With new technology there are always a number of challenges and potential risks for whose management no precedent exists. The risks associated with the capsule are identified above and encompass such events as decompression of the pod to mechanical failure of the pod levitation or propulsion system, as well as fire in the capsule.

With the continued advancement of the capsule design the risks and uncertainties will continue to evolve. However, a number of factors (e.g. a pressurized capsule environment) will remain key components of the vehicle design and risk reduction or mitigation associated with such elements should be given consideration.

Infrastructure

- Hazards and Threats covered: H03, H08, H09, H10, H12, H14, H15, H17, H18, H19, H25, T03 and T06

Hyperloop will need to operate in a special environment that has been artificially created in order to realize the proposed benefits of the system. Creating and maintaining any artificial environment comes with a number of risks and challenges and some of these, such as maintaining a suitable power supply, monitoring the structural integrity of the tubing and deterring trespassers, have been identified in the hazards and threats.
Although most of the components proposed in the infrastructure design are not new technology, using them in the proposed combination represents an approach not previously implemented in a real-world scenario. Further testing and greater understanding of how the design of tube body, pylons, and foundations will withstand extreme weather conditions or natural disasters will be necessary to avoid significant risk to users.

<table>
<thead>
<tr>
<th>System Components</th>
<th>Hazards and Threats covered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H08, H09, H11, H12, H13, H16, H17, H20, H24, H25, H27, H33 and H34</td>
</tr>
</tbody>
</table>

The Hyperloop system will utilize several important components, chief among these is the need for vacuum pumps to maintain a low-pressure environment as well as a magnetic levitation system to provide pod levitation and potentially propulsion. The risks associated with the system components include the shutdown of devices interrupting service, deformation or incorrect performance of the systems and failure of the system during active operations.

The risks associated with such incidents vary greatly in terms of impact and potential hazard/threat to human life. It will be important for the Hyperloop technology companies to continue demonstrating the effectiveness and safety of such components as the technology matures.

Challenges still exist, such as addressing the need for maintaining and monitoring a constant vacuum over long stretches of tube and designing for redundancy of pumps to eliminate pump failures either in the tube or at the airlocks. As demonstrated in Section 3 - Hyperloop Concept and Engineering, the technology readiness of several of these systems is still relatively low and further information, design and testing will be required to demonstrate viability of the components.

<table>
<thead>
<tr>
<th>Communications</th>
<th>Hazards and Threats covered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H17, H21, H22, H23, H24, H31 and H33</td>
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Hyperloop technology companies have stated that one of the advanced features of the system will be the high level of automation. Even a relatively simple route between two locations will involve a large number of processes and procedures.

Successful operation will rely on effective and reliable communications systems and software that can effectively manage the movement and monitoring of the system. Identified hazards are predominately based on communication system failure that either leaves the pods unable to communicate effectively or switches and airlocks disconnected from the system.

Switches and airlocks are two of the more complicated and critical components of the Hyperloop network and will perform some of the most delicate and important system operations, so any loss of communication to these could have significant risks and operational impacts.
As both high-speed switching and commercially viable airlocks are still untested components, further design and development will be required to understand the full range of risks. The ability to communicate at all times with these components will be essential so redundancy procedures will be an unequivocal requirement.

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<thead>
<tr>
<th>Security</th>
<th>Hazards and Threats covered</th>
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<tbody>
<tr>
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<td>H31, H34, T1, T2, T3, T4, T6 and T7</td>
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The security of any high-profile transportation system is, unfortunately, an essential consideration in the current global environment. Hyperloop as a new technology will present several new security challenges, including how to avoid tampering or trespass in the tube system, passenger issues within the pod, and evacuation procedures.

The concept of pressurized capsules is not new to the transportation industry, however the constraints of being enclosed in a tube with no alternative route options is an added factor. As security procedures for transportation continue to evolve, Hyperloop operators and regulators will need to stay abreast of industry changes and new practices.

<table>
<thead>
<tr>
<th>Environmental Factors</th>
<th>Hazards and Threats Covered</th>
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<td>H18, H19 and T3</td>
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The introduction of Hyperloop infrastructure into a corridor will require consideration given to the surrounding environment. Hyperloop tubes are most likely to be elevated along the majority of the route, with tunnelling possibly occurring in dense urban environments. It will therefore be important to ensure the corridor (right of way) for the Hyperloop route is kept clear of obstructions and that suitable measures are in place to avoid any potential development impact on the corridor.

Although a limited number of environmental risks are associated with Hyperloop unknown factors remain regarding the impact of the system on the environment and what other risks might arise. These are likely to be better understood with the development of larger scale testing facilities.

4.3.2 Regulations Comparison

Identification and categorization of the hazards and threats has demonstrated significant uncertainty regarding how Hyperloop systems will operate. A number of safety concerns have the potential for significant damage to property and possible serious injury or loss of life. These hazards and threats need to be mitigated or eliminated to ensure the system operates with the least possible risk to users, operators, and those in proximity to the system.

The Canadian framework governing existing transportation modes provides some examples of how each of the four current modes of transportation deals with the hazards and risks associated with their operation.
Hyperloop, as a new concept, is unlikely to fit under one of the existing modes and it is therefore recommended that a governance framework be established to guide it.

At this early stage in the product’s lifecycle there are many unknowns, including those pertaining to regulations. The hazard and threat assessment has identified some areas where regulation could be considered to reduce risk.

The following section examines these and considers what the risk is, why it is important, and outlines how similar risks in other modes have been dealt with. It is important to note that it is not possible to simply apply the same regulations from other modes to Hyperloop. However, as discussed in previous sections, Hyperloop uses some of the concepts, approaches, and similar technology to those in rail and aviation and, as such, the regulatory frameworks for these modes provide some useful insight.

**Transport Canada’s Role**

Transport Canada uses a combination of legislation, regulations, rules, standards, and guidelines to fulfill its mandate of ensuring the safety and security of passengers and goods as well as reducing the environmental impacts of the transportation sector. Generally speaking, Transport Canada’s safety and security framework is divided into four distinct modes: civil aviation, rail, marine, and motor vehicle.

Each of these modes has its own distinct legislative and regulatory frameworks. Federal statutes, such as the *Aeronautics Act* and the *Railway Safety Act*, among others, must be passed by Parliament. They set important requirements and provide the Minister or Governor in Council with authority to make certain regulations for the purpose of providing details that give effect to the policy established by the statute.

While it is evident that Hyperloop can be classified as a mode of transportation, the technology does not currently fit within any existing modal regime. Because Hyperloop is largely at the conceptual and small-scale testing stage, it is vital that regulatory considerations are developed based on real and potential risks, but further research and consultation are needed before decisions on policy directions and regulatory frameworks can be made.

**Hyperloop Governance and Guidance**

The following section identifies a number of areas where guidance or governance from an external body might provide insights to mitigate or remove risk (Transport Canada is just one of the agencies that might be responsible for enacting any of the guidance or governance, it is expected that other agencies will be involved in the processes). The list is not exhaustive, and the current state of Hyperloop technology development means that this list will change and update with time.

| Reserve Oxygen Supplies | Vehicle Design | Hazards and Threats Covered | H01, H02, H04, H05 |
Depressurization of the tubes and the necessity for oxygenated capsules presents the primary potential risk/hazard to passenger safety. The PHA and TVA identify multiple hazards and threats requiring action be taken to ensure sufficient oxygen supply in the Hyperloop capsules. Based on AECOM’s analysis, maintaining reserve oxygen supplies to serve in the event of any emergency is deemed critical.

Therefore, it is recommended that the system’s pressurised capsules are equipped with an onboard oxygen system, which should also comprise a reserve system in the event of primary system failure or occupants requiring more oxygen than usual due to delay in travel time.

The challenge of ensuring sufficient oxygen for passengers is not unique to Hyperloop. Reserve oxygen supplies are a requirement in the aviation industry since aircraft fly at high altitude where pressurization is required to maintain the health and comfort of occupants. Thus, oxygen supply poses an important factor in guarding the safety of air passengers.

To address this hazard, Part 6, subpart 5 – Division II of The Canadian Aviation Regulations (SOR/96-433) sets requirements for the availability of oxygen supply in the event of pressure fluctuations within the aircraft (see subsections 605.31 (1) and (2) for Oxygen Equipment and Supply).

<table>
<thead>
<tr>
<th>Capsule Maintenance</th>
<th>Vehicle Design</th>
<th>Hazards and Threats Covered</th>
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<td></td>
<td></td>
<td>H01, H02, H03, H04, H05, H06, H07, H10, H11, H21, H22, H23, H26, H28, H33, H34 and T05</td>
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The capsule is a key factor of the Hyperloop system and is expected to be a well used component. Ensuring the pod’s systems and condition are well maintained will be critical to passenger safety. It is recommended that this be achieved through the development and implementation of a maintenance inspection program that would check and test the various components of the pod.

Improper/inadequate pod maintenance could have a potentially catastrophic impact on the operations of the system as a whole as it could cause a range of hazards and threats, such as stalling while in operation. The provision of adequate maintenance facilities and yards would be important in ensuring safe maintenance of the equipment and reducing the risk of personnel injury, therefore protecting the system’s operation.

Maintenance frameworks exist for a number of other transportation modes (e.g. air and rail transportation) and can provide insight into how these modes have addressed maintenance concerns.

- **The Aeronautics Act (R.S.C., 1985, c. A-2)**: Section 4.9 – states the general regulatory powers of the Governor in Council in creating regulations concerning aeronautics, including (but not limited to):
  - accreditation and/or licensing;

- design, manufacture, distribution, maintenance, approval, installation, inspection, registration, licensing, identification and certification of aeronautical products; and,

- design, installation, inspection, maintenance, approval, and certification of equipment and facilities used to provide services relating to aeronautics.

- **Technical Airworthiness Authority (TAA) Advisory**: the authority provides guidance on categorization and design changes and determines the route to certification of a design change in the fuselage. This authority provides guidance related to the *Technical Airworthiness Manual* (TAM) (regulatory reference 3.2.a) rules and standards for categorizing design changes as either major or minor. According to the TAA, the fuselage skin material should undergo and pass testing for fire protection, weight loading, as well as operational circumstances (e.g. altitudes, weather conditions, etc.) in order to be deemed appropriate for use in the body of aircraft.

- **Fuselage Skin Quality (FSQ) – QD 4.650CS**: is a document issued in 2019 by Airbus Canada. It states that the specific criteria against which fuselage conditions are tested at Airbus Canada must include:
  - Abrasion; Blisters (Bond and Core); Chatter Marks; Corrosion; Dent; Edge Condition; Interleave Fretting; Gouges/Scratches; Pits; Sanding Marks; Cracks/Lamination; Roll Marks; Stains/Discoloration/ Mottling/ Streaks; Water Stains; Suction Cup Marks; Kinks; Quench Marks; Flatness; and Orange peel.

- **The Canadian Aviation Regulations (SOR/96-433), Part V – Airworthiness**: Subpart – 71 establishes requirements for aircraft maintenance performance in subsection 571.02, while subsection 571.03 sets requirements for the recording of maintenance work.

The various documents mentioned above identify some of the areas where legal or policy frameworks have been used to regulate and monitor various components. The processes and structures identified could help provide an understanding of the framework components Hyperloop operators might need to implement in order to monitor performance and set maintenance standards. It is recommended that a potential framework consider the following:

- What inspections will be required for pods operating on Canadian soil, including defining their state and maintenance needs;

- How will inspections of pod batteries be conducted and what standards might they be required to meet; and

- Is there a need for a standardized quality control procedure for all maintenance activities associated with Hyperloop technology?
The Hyperloop infrastructure represents a major part of the complete system and could cover hundreds of kilometres between stations.

Monitoring and maintaining the infrastructure will be a major challenge but will be necessary to mitigate several identified hazards relating to the deterioration of the infrastructure. Failure to maintain the infrastructure to construction standards could lead to operational issues or even system shutdowns.

The importance of infrastructure maintenance is recognized in other transportation modes, which have their own processes in place for monitoring and management. Below are some examples of how other modes approach infrastructure maintenance:

- **The Railway Safety Act (R.S.C., 1985, c. 32):** Part II of the Act is titled “Operation and Maintenance of Railway Works and Equipment”
  - Section 17.2 asserts that in order to operate and maintain a railway or equipment, a valid railway operating certificate is required.
  - Section 18.1 provides the Governor in Council authority to make regulations (a) respecting the operation or maintenance of line works, and the design, construction, alteration, operation, and maintenance of railway equipment.

The impact of the neighbouring environment on the Hyperloop infrastructure and corridor will require careful consideration in the planning and design of routes, as well as regular monitoring. Hazards and threats identified range from impact or encroachment by the natural environment, development or other infrastructure, to major incidents such as environmental disaster or force majeure events. These can have operational impacts on the Hyperloop system and should be monitored and managed where possible.

Such environmental factors and corridor monitoring practices are not unique to Hyperloop and industries such as aviation and rail can provide examples of how to handle such risks.

- **The Canada Transportation Act (S.C. 1996, c.10):** this Act contains several sections dealing with impacts of development and operations on the surrounding environment. Section 95 of the Canada Transportation Act (S.C. 1996, c.10), lists the following powers, which may be exercised by railway companies:
- Make or construct tunnels, embankments, aqueducts, bridges, roads, conduits, drains, piers, arches, cuttings and fences across or along a railway, watercourse, canal or road that adjoins or intersects the railway;

- Divert or alter the course of a watercourse or road, or raise or lower it, in order to carry it more conveniently across or along the railway;

- Make drains or conduits into, through or under land adjoining the railway for the purpose of conveying water from or to the railway;

- Divert or alter the position of a water pipe, gas pipe, sewer or drain, or telegraph, telephone or electric line, wire or pole across or along the railway; and

- Do anything else necessary for the construction or operation of the railway.

<table>
<thead>
<tr>
<th>Energy Supply</th>
<th>Vehicle Design</th>
<th>Infrastructure</th>
<th>System Components</th>
<th>Communications</th>
<th>Hazards and Threats Covered</th>
<th>H08, H09, H11 and T04</th>
</tr>
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</table>

The hazards and threats identified reveal a number of policy areas that would be impacted by inconsistency or failure in power supply. The operation of the pods, low pressure environment, communication protocols, and infrastructure are likely to be heavily reliant on power supply.

Little is known about how the pods would behave if power was cut during travel at intended velocities. Also discussed was what might happen to the operation and components within the network if power supply was interrupted. With the infancy of high-speed switching, what might the impact of a power loss to the switch mean for its operation? There are numerous uncertainties, but it seems likely that backup power supplies will be required for a number of the elements and systems.

The provision of back up systems is not unique and other transportation modes, such as air, require backup systems to allow operations to continue.

- **The Canadian Aviation Regulations Part VI, Subpart 2, Division II** sets requirements for procedures, equipment standards and checklists to allow for safe operation, even in the event of:
  - emergency operation of fuel, hydraulic, electrical and mechanical systems, where applicable;
  - emergency operation of instruments and controls, where applicable;
  - engine inoperative procedures; and,
  - any other procedure that is necessary for aviation safety.
Passenger security is one of the most important elements of any transportation system and ensuring that passengers are safe from external threats and other travellers is essential to maintaining public safety.

To provide an environment where passengers can feel safe, security screening is recommended to detect any potential threats. Similarly, the screening of freight and goods is also recommended.

Internal security measures could be met by implementing proper passenger screening practices to prevent passengers entering the system with potentially harmful materials. Similar screening procedures of freight and goods at the point of entry could also be conducted to reduce the risks.

The screening of passenger and freight is a practice mainly expected to take place at terminals prior to entering the Hyperloop pods. Passenger screening practices can include identifying:

- Passengers carrying materials that could pose a security risk;
- Passengers with easily transmissible communicable diseases; and
- Passengers deemed a threat to society (e.g. suspected terrorists, those with outstanding arrest warrants, etc.).

Freight screening practices can include identifying:

- Dangerous or prohibited materials;
- Cargo not properly packaged or contained; and
- Freight that does not have the correct shipping, customs, or general clearance for travel.

Legal frameworks for screening are currently employed in other modes of transportation (e.g. air). A number of different Acts and regulations govern the screening of air travel, a sample of which are noted below:

- **Canadian Air Transport Security Authority Act (S.C. 2002, c. 9, s. 2) Section 27 – Safety of the Public:** States that the provision of screening at an aerodrome is conclusively deemed for all purposes to be a service that is necessary to prevent immediate and serious danger to the safety of the public.

- **Canadian Air Transport Security Authority Act (S.C. 2002, c. 9, s. 2) Section 34 – Regulations:** Provides authority for the Governor in Council to make regulations:
  - designating aerodromes for the purposes of this Act;
  - requiring the Authority to provide to the Minister such information as the Minister may request.
• **The Secure Air Travel Act (S.C. 2015, c. 20, s. 11)**[^94]: is intended to enhance security relating to transportation and prevent air travel for the purpose of engaging in acts of terrorism.

• **The Air Passenger Protection Regulations (SOR/2019-150)**: Sections 1 through 46 sets requirements relating to liability, passenger needs, customer charter and general customer-orientated and ability-related facilities, accessibility and communication that could inform the regulatory requirements for Hyperloop technology.

Modern-day security challenges can extend to any part of the transportation network. In order to protect the entire system, security measures beyond the passenger access/egress points are recommended. The novelty of the Hyperloop system makes it an inviting target for nefarious acts and procedures for identifying and deterring threats will form an important part of the system-wide security.

Potential threats are not fully realized as the system has yet to be implemented in a real-world scenario. However, factors such as external access to tubes, direct assaults on the tube and targeting ancillary components have also been discussed as potential security concerns. Such concerns make maintaining external security and using detection measures such as real-time monitoring of the tube infrastructure, necessary.

Other transportation modes must already contend with external events requiring security measures. The following details one of the measures used by the air sector:

• **The Aeronautics Act (R.S.C., 1985, c. A-2) – Section 4.72 – Security Measures**: this section provides the Minister with the power to make and carry out security measures. In summary the section provides wide-ranging powers to take whatever measures are deemed appropriate to protect passengers, staff and the industry as a whole.

Several hazards and threats, discussed in the PHA and TVA, could potentially result in a total or partial shutdown of the system.

It is recommended that a series of procedures and processes be put in place to provide a structured approach to managing the event and ensuring the safety of passengers, staff and anyone in proximity to the system.

Emergency procedures are an integral part of Canadian transportation frameworks. In a possible regulatory framework for Hyperloop, considering how the system will respond to an emergency is recommended due to its intertwining nature and complexity. When a system shuts down, the framework should consider factors relating to the impacts of shutting down one part of the system in its entirety.

The air industry in Canada has a number of guidance and procedure documents that provide information on the management of system shutdowns during operation, for example:

- **The Multicrew Aircraft Standard Operating Procedures Checklist and Guidance Material** provides detailed operating instructions on how to handle emergency shutdown procedures in flight, during take-off (7.6), due to fire in flight (7.7), or for other shutdown reasons (7.8).

<table>
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<tr>
<th>Capsule Evacuation</th>
<th>Vehicle Design</th>
<th>Hazards and Threats Covered</th>
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<tbody>
<tr>
<td>Security</td>
<td></td>
<td>H01, H02, H04, H05, H06, H11</td>
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</table>

Various emergency scenarios could arise that require evacuation of the capsule. These could either take place at a station or within the tube, both of which present a number of different challenges. The development of procedures and guidelines on the management of capsule evacuation in any operating environment is recommended.

With its low-pressure tube environment, Hyperloop presents some unique challenges to evacuation and thus far, no proposed approach has been agreed upon by the Hyperloop companies. Given the unique elements of the system it is likely some specific measures will need to be included in the evacuation procedures for Hyperloop. Both air and rail have evacuation procedures that offer some insight.

- **The Aeronautics Act (R.S.C., 1985, c. A-2) – Section 4.76 – Emergency Directions**: Provides the Minister with the authority to direct evacuation, diversion and movement of aircraft/aviation facilities/persons in the event of an immediate threat to aviation security.

- **The Canadian Aviation Regulations (SOR/96-433) – Part VI – General Operating and Flight Rules**: Subpart 4 – sets requirements for General Operating and Flight Rules including the minimum:
  - Number of flight attendants (CAR 604.221);
  - Emergency Features (CAR 604.222); and,
  - The Demonstration of Emergency Evacuation Procedure (CAR 604.223).
• **Flight Attendant Training Standards (PT 12296E):** was issued by Transport Canada in 2008 and sets crew responsibilities and procedures relating to the different types of evacuation situations.

• **The Prevention and Control of Fires on Line Works Regulations**\(^95\): These regulations provide railway companies with a framework for fire incidents and set out the planning and preventative measures required to reduce the likelihood of fires caused by railway operations. They apply to all federally regulated railway companies, including local railway companies operating on a federal track. Requirements include:
  
  ▪ A fire preparedness plan that includes procedures for:
    - extinguishing or controlling a fire;
    - internal notification; and,
    - fire services notification.
  
  ▪ A fire hazard reduction plan that includes:
    - a process for identifying fire hazards;
    - measures for reducing or eliminating fire hazards; and,
    - measures to take for each fire danger level used in the Canadian Wildland Fire Information System (CWFIS) when railway companies conduct high-risk work.

Railway companies must also provide:

  ▪ Mandatory training for railway employees who perform high-risk work to ensure that fire extinguishment equipment and fire suppression equipment is used by trained individuals.
  
  ▪ Fire suppression equipment to be used by employees and contractors who perform high-risk work as set out in the railway company’s fire hazard reduction plan.
  
  ▪ Companies are required to keep relevant documentation (e.g. Preparedness Plan, contract for fire service and other) for five years from creation and provide to Minister of Transport upon request.

<table>
<thead>
<tr>
<th>Communications Protocols</th>
<th>Communications Hazards and Threats Covered</th>
<th>H06, H07, H08, H09, H11, H21, H22, H23, H24, H31, H32, H33, H34 and T7</th>
</tr>
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</table>

Hyperloop is a novel mode of transportation highly dependant on technological innovation and data communication.

The operational model of Hyperloop proposes multiple capsules moving at high operating speeds, so it is recommended that mitigating steps be taken to prevent/avoid hazards arising from compromised transmission of information. Central to this will be the need for split-second communication system-wide. The system will likely require a structured procedure for how pods will be dispatched into the tubes and at what headways, monitoring of all the pods in the system in real-time and detection of any malfunctions.

Communications are an important part of other modes such as air and rail and these can provide some examples of how other transportation sectors have handled the management of communication protocols.

**The Canadian Rail Operating Rules**\(^96\): These rules are intended to enhance railway safety during operations. They cover a wide range of topics from employee responsibilities, signalling equipment, procedures for safe train movement, to dealing with accidents. In Canada, a Centralized Traffic Control (CTC) system is adopted to ensure the proper dispatching of trains on any rail network. The CTC rules are covered in Rules 60-576. They apply to limits specified in the timetable (i.e. a train’s predefined schedule) or special instructions and are overseen by a Rail Traffic Controller (RTC). Block signals govern the operation of trains or transfers. The RTC issues instructions as required. The CTC is used to consolidate train routing decisions. In the past, these decisions were carried out by local signal operators or the train crews themselves. The system consists of a centralized train dispatcher’s office that controls railroad interlockings and traffic flows in portions of the rail system designated as CTC territory, to avoid unreasonable wait times and congestion or blockage of the network. The application of CTC ensures smooth and safe railway operations.

- **Railway Signal & Traffic Control Systems Standards (TC E-17)**\(^97\): These standards apply to all railway companies falling under the jurisdiction of the Minister of Transport pursuant to the *Railway Safety Act*. The standards ensure that railway signal and traffic control systems are installed, modified and maintained in a safe manner. For example:
  - Railway signal and traffic control systems shall be designed using failsafe principles.
  - Railway signal and traffic control systems shall, so far as possible, be arranged so that failure of any part of the system shall cause affected signals to give the most restrictive indications that the condition requires.
  - All control circuits, the functioning of which affects safety of train operation, shall be designed on the closed-circuit principle.
  - Railway signal and traffic control systems shall be so interconnected that aspects to proceed cannot be displayed simultaneously for conflicting movements, except that opposing signals may indicate “proceed at restricted speed” at the same time for switching movements only.


\(^97\) [https://www.tc.gc.ca/media/documents/railsafety/E17e.pdf](https://www.tc.gc.ca/media/documents/railsafety/E17e.pdf)
- In signalled territory, track circuits and route locking shall be provided to prevent operation of power switches, derails or movable-point frogs, underneath or directly in front of a train.

- At interlockings, approach or time locking shall be provided in connection with signals displaying aspects more favourable than “proceed at restricted speed.” In Centralized Traffic Control systems, approach or time locking shall be provided for all controlled signals.

- Each signal shall be located with respect to the next signal, or signals, in advance, which governs train movements in the same direction so that a restrictive aspect can be complied with by means of a brake application, other than an emergency application, initiated at such signal.

### Infrastructure Design

| Infrastructure Design | Infrastructure | Hazards and Threats Covered | H12, H13, H14, H15, H19 |

The design of the Hyperloop tube and network system will involve a comprehensive planning and design process. This will include developing the design through initial, preliminary and detail design stages to satisfy the planning agencies involved. The risks associated with failure to properly plan and design the system could be catastrophic.

Although established procedures exist for the monitoring and quality assurance of transportation infrastructure design and construction, Hyperloop presents a number of unique elements these processes might not cover. This suggests certain Hyperloop-specific processes for assessing the design and construction process might be required.

The need to assess the viability and safety of a transportation mode is not unique. The aviation industry operates a certification program in Canada to assess the airworthiness of any new aircraft design.

- **The Canadian Aviation Regulations Part V – Airworthiness** sets requirements relating to a range of new aircraft and aircraft components to:
  - Review and verify design and performance data
  - Supervise and perform ground and flight tests
  - Award Transport Canada Type Certificates

### Onboard Facilities

| Onboard Facilities | Infrastructure | Hazards and Threats Covered | H08 and T2 |

There has been considerable debate over the need to provide services on-board Hyperloop pods. Some developers feel that the envisioned journey lengths don’t necessitate the provision of facilities such as washrooms, refreshments or even entertainment, while others have already begun to showcase concept pods that include such items.
Risks associated with the provision of such services could include the effect of sudden acceleration or deceleration on those not seated. However, equally challenging could be the consequences of not providing in-capsule washroom facilities which could negatively impact passenger comfort.

As travel at the envisaged speeds has yet to be tested, it is not possible to assess what the actual impacts to passengers could be when moving around in the capsule. Understanding these risks and challenges will be important in determining the direction to take in offering the services or not.

4.4 Outstanding Areas

The previous section examined areas of the Hyperloop system identified as presenting risks. The ways in which other transportation modes deal with similar risks were also discussed. While a number of the system elements and associated risks are common to multiple modes, several hazards or risks are unique to Hyperloop. These are discussed below in more detail.

As with any emerging technology, regulations and standards can play an important role in facilitating the design and development of the components and/or system. This becomes more challenging when the potential risks are unique to the planned system, as any guidance or regulation needs to be formed with a full understanding of how the component is meant to function and consideration of the economic impacts of such measures.

As a number of the Hyperloop components are either in need of proof of concept or further refinement, the development of any guidance will be an iterative process. However, preparing an innovation-friendly regulatory framework at an early stage could support the development of these components.

Hyperloop technology companies believe their capsules will be capable of travelling speeds no other land-based transportation mode can match. Part of the system’s attraction are the minimal travel times from origin to destination. In order to achieve these travel time savings, the capsules will need to travel at their maximum speed for as long as possible along the route.

The technology options being explored to create and maintain momentum have not previously been applied in any similar scenarios and offer the potential for far greater acceleration and deceleration than other modes are capable of. While it can accelerate to and break from its cruising speed very rapidly, the G-Force that would be exerted by the system may be greater than the human body can handle.98

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This raises a previously unencountered challenge where the impact of acceleration and deceleration on the human body will be a significant consideration to be addressed. Questions arise as to what limits should be placed on acceleration to prevent injury to passengers, that offer suitable protection while still maximizing the travel time benefits of the system.

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Environmental Factors</th>
<th>Hazards and Threats Covered</th>
<th>Unknown at this level of development</th>
</tr>
</thead>
</table>

The current approach to powering Hyperloop is to utilize electrical energy, either through onboard batteries or through the adjacent infrastructure. At present, the hope is that power could be obtained from green energy sources such as solar power, although this idea is still very much under development. Noise and vibration emissions from the system are also unknown at this point and require further testing before they can be fully understood.

The question of emissions will be a contentious one, with many of the technology companies hailing the system as emission-free. At present, the actual emissions of the system are not fully known, and further testing and examination is required. A number of statutes and regulations exist regarding protection of the environment and the need for infrastructure to minimize its environmental impact. For example:

- **The Canadian Environmental Protection Act** (1999, c. 33) 99: this Act sets requirements for pollution prevention and the protection of the environment and human health in order to contribute to sustainable development.
  - The initiation of an Environmental Protection Plan when planning for the infrastructure; e.g. pylons, tunnels, terminals, electricity grids, etc.;
  - Ensuring equipment emissions meet the standards and do not emit GHG emissions or pollute the environment.;
  - Ensuring the new infrastructure does not compromise the quality of the environment by confirming the pod, tubing, batteries, and electrical grids meet the national emissions standard.; and,
  - Ensuring that proper environmental data and research have been conducted in feasibility studies to reduce the possibility of disturbing the environmental ecosystem.

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Friction

Vehicle Design

Hazards and Threats Covered

H03, H07, H08, H10, H11, H16 and T4

The impact of possible fire and/or water in the capsule or the pod could be catastrophic. Friction build-up between the pods and tubes could result in sparks and potential fires. A degree of uncertainty remains about what friction complications could occur at the planned operating speeds and how they might be mitigated. This will only be addressed as the technology continues to develop and potential friction concerns emerge.

Given the concerns surrounding friction, maintaining the magnet gap between vehicle motors will be an important factor in mitigating the potential hazard of friction build-up. The potential for friction-related risks is not yet known, and further testing and monitoring will be required before any mitigation plans can be developed.

High-Speed Switching

Infrastructure

System Components

H12, H20, H24

High-Speed switching is one of the more unique challenges raised by the Hyperloop concept. Advancement of the concept has led Hyperloop companies to identify an opportunity to develop a network of connections where pods might change tubes midway through a journey to access an alternative destination.

Given the anticipated speeds the pods might reach, these switches present a new, previously unimagined, challenge. Understanding how the switches work, the risks involved in changing tube guideways at such speeds, and the various operational complexities will take time given the relative underdevelopment of the switches at present.

There will need to be significant research, design work, and testing of the switches before any decisions regarding risk mitigation can be made.

While high-speed switches present a new challenge, switching guideways is not a new concept. For railways there are several existing frameworks that offer insights into the topic of switching:

- **Rules Respecting Track Safety TC-E-54**: prescribe safety requirements and set limits for federally governed railway tracks across Canada.

  They define the baseline track geometry requirements used by all freight railway companies in Canada.

• **Rules Respecting Railway Clearances TC E-05**: the standard railway clearances, outlined in Rule 3.1, notes:
  - Industrial sidings shall afford the minimum clearances as set out in Diagram 4, where required to be different from those set out in Diagram 1;
  - A lateral allowance for track curvature of 25.4 mm (1 inch) per degree shall be provided;
  - All clearance diagrams shall be perpendicular to the plane of the top of the rails;

• **The Canada Transportation Act – Section 127**: This section sets requirements regarding interswitching between railway companies.

### 4.5 International Review and Perspective

Hyperloop technology is in its early stages, as such there is very little regulation and guidance for operation. However, several initiatives have been undertaken to begin the process of assessing and classifying the risks and requirements for regulation. **Table 24** identifies organizations and resources that have taken steps to develop frameworks aimed at standardizing and regulating Hyperloop systems. These organisations are located in North America and Europe which, to date, have been at the centre of Hyperloop technology development.

**Table 24: List of International Organisations/Resources involved in Hyperloop Regulation**

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Reviewed Regulation / Act / Standard Body / Study and/or Other Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Future of Hyperloop Study by Delft Hyperloop</td>
</tr>
<tr>
<td>02</td>
<td>The Non-Traditional and Emerging Transportation Technology (NETT) Council</td>
</tr>
<tr>
<td>03</td>
<td>The Joint Technical Committee (JTC 20) on Hyperloop Systems</td>
</tr>
<tr>
<td>04</td>
<td>European Hyperloop Development Initiative lead by Zeleros</td>
</tr>
<tr>
<td>05</td>
<td>Hyperloop Transportation Technology and Tüv Süd Guidelines</td>
</tr>
</tbody>
</table>

The steps these organizations have taken provide useful insight into how other governing authorities might proceed in preparing for the implementation of Hyperloop.

Further information on each of the organizations/resources is provided on the proceeding pages.

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101 The diagrams referred to can be found on Pages 6-10 in [https://www.tc.gc.ca/media/documents/railsafety/TC_E_05e.pdf](https://www.tc.gc.ca/media/documents/railsafety/TC_E_05e.pdf)
4.5.1 Future of Hyperloop Study by Delft Hyperloop

AECOM reviewed the *Future of Hyperloop Study by Delft Hyperloop*. The results were presented as a report in June of 2019 to the Dutch Ministry of Infrastructure and Water Management. The paper discussed a number of areas pertaining to Hyperloop including Safety, Security, and Regulatory (Chapter 12: Safety Analysis and Chapter 13: Regulatory Implications of the Delft Hyperloop Study) and offers some insightful international perspectives. The report includes a chapter (Chapter 14: Future Points of Notice) offering thoughts on the challenges surrounding standardization, policymaking, financing, etc. relating to Hyperloop technology expansion from a European perspective. Key observations from these three chapters are discussed below.

**Chapter 12: Safety Analysis**

The Study discussed the importance of safety as a critical requirement for a Hyperloop system to be realized and for its envisioned widespread implementation.

The safety of the system must be guaranteed to at least the same level as other high-speed modes of transportation. Lessons learned from other modes of transportation are as follows:

- Large accidents can hinder, even prohibit, the development and implementation of transportation innovations (e.g., the TransRapid magnetic levitation train in 2006 in Lathen, Germany; and the 2000 Concorde aircraft accident).

- Track curvatures must be adequately designed for high-speed modes (e.g. the 2013 train derailment in Santiago de Compostela).

For the safety analysis, a combination of methods is used. Elements of *a) Failure Mode and Effect Analysis (FMEA)* and *b) a Hazard and Operability study (HAZOP)* are used in the Hazard Analysis. The analysis was undertaken to identify the main risks of all subsystems (pod structure, tube structure, vacuum pumps, airlocks, propulsion, levitation, braking, wheels, high-speed switches, pod equipment, communication, human operations and external influences), causes and consequences of the hazards, and mitigation methods. The outcomes of the analysis are as follows:

- Most risks are related to the communication subsystems. When travelling at speeds over 1000 km/h with a 30-second headway, location detection of all pods needs to be extremely reliable.

- Communication technologies need to be tested thoroughly in a high-speed test facility (preferably underground) to ensure reliability.

- A redundant power supply system in the tubes, for communication, and the pods, for braking, is required to avoid pod crashes.
• The deterioration of pod doors poses a large risk in exposing passengers to the vacuum environment. Doors must open inwards (taking advantage of the pressure difference for better door sealing) to minimize the likelihood of failure.

• Black-swan risks (i.e. risks that have an extremely small likelihood but catastrophic consequences) are concluded to all be related to tubes. Tube deformation and external factors, such as earthquakes, flood, and extreme temperatures, would have major consequences.

After performing the Hazard Analysis, the Study suggests the concept of “Safe Haven Design”. The Safe Haven concept is based around the principle that, in case of an emergency, a vehicle can make its way to a “Safe Haven”, which will provide a safe exit to the passengers. The Safe Haven concept guarantees a sufficient level of safety while minimizing the investment cost for emergency exits. A Safe Haven must fulfill the following requirements:

• Provide safe evacuation time in case of an “in-pod emergency”;

• Provide safe evacuation time in case of a “brick-wall emergency”;

• Minimize impact on operability of the system in case of an emergency;

• Must be designed to be as small as possible to minimize the investment cost.

To design the system, the Study considered two emergency scenarios: a) “in-pod” emergencies for emergencies inside a pod that threaten the safety of passengers but do not impact the functionality of the rest of the system; and b) “brick-wall” emergencies where safe passage of a pod past a certain part of the tube is impossible. In order to design a Safe Haven framework, as shown in Figure 23102, the following design parameters need to be considered to ensure sufficient emergency egress measures:

• Intermediate Safe Haven distance: this distance is governed by the acceptable evacuation time for passengers in the case of an “in-pod emergency”, based on the assumption that pods are always able to travel forwards and backwards in emergency situations. This time must be determined as an industry standard.

• Safe Haven pod capacity: the minimum capacity of a Safe Haven must be sufficient to include at least one pod at a time. It is recommended that the Safe Haven is configured as a separate tube section to minimize operational disruptions during “in-pod emergencies”.

• High-speed switch length: the switch length must be sufficient for a pod to come to a complete standstill at the Safe Haven; thus, higher cruising speeds mean higher switch lengths.

102 https://drive.google.com/file/d/1TdhhXiGgjKXMnKSzqHFz6AObcC1qQLOr/view; Figure found on page 57/82 of The Future of Hyperloop Study by Delft Hyperloop, 2019.
Chapter 13: Regulatory Implications

The study emphasized the following three items, (I) Standardization, (II) Legislation and Policies and (III) Certification, when it came to the planning of a Hyperloop in any country:

(I) **Standardization** – In the Literature Review section, it was discussed that several companies are now investing in the design and testing of Hyperloop technology. The Future of Hyperloop Study emphasized the importance of requiring standardization of the Hyperloop concept in order to increase interoperability between countries. Parameters leading to standardization (e.g. tube diameter) must be determined in collaboration with governing bodies. Multiple technologies must be researched and developed first to determine the best option for use in the eventual standardized Hyperloop system. The Future of Hyperloop Study emphasized the importance of a single European standard to improve interoperability, but cautioned against this too early in the process, as multiple techniques must be researched first in order to develop their potentials.
(II) **Legislation and Policies** – Legislation will be necessary to guarantee safe Hyperloop operations. Existing modes of transport share certain design aspects with Hyperloop (e.g. the pressure vessel of the pod is similar to that of an airplane fuselage). Thus, the study theorizes that legislature for Hyperloop can be derived from existing transportation regulations and adjusted accordingly. Hyperloop technology must be proven before a complete legislation framework can be developed. However, it has been observed that in modern transportation systems, infrastructure planning and arrangements always precede the adoption of vehicles. Early support of public policy for Hyperloop infrastructure could be essential for its implementation, as it can potentially incentivize and speed up the development process.

The Delft Hyperloop study recommends that regulations concerning safety standards for Hyperloop be determined at the European level, as Hyperloop’s unique vacuum and high-speed characteristics will require specific safety regulations.

(III) **Certification** – Similar to legislation, various norms and standards for certification can be derived from railway and aircraft certification. In the study, examples of railway standards that could inform the regulatory requirements to Hyperloop technology include:

- V-model approach used in EN 50126 railway certification standard;
- Technical Specifications for Interoperability (TSIs) for infrastructure, energy, rolling stock, control command and signalling, and maintenance and operation;
- TSIs share similarities with Hyperloop technology including Safety in Railway Tunnels, Control; and,
- Command and Signalling, Persons with Disabilities and with Reduced Mobility.

The study identified two possible certification methods:

- Allow multiple organizations to carry out the certification (similar to railroad standards);
- Only allow one single organization responsible for certification (e.g. European Union Aviation Safety Agency).

In addition, the study recommended the early determination of certification standards so that knowledge of the certification goals can inform the design process, thus reassuring and incentivising the multiple stakeholders required for bringing the concept to actuality. Test facilities need to be constructed to demonstrate that Hyperloop can safely operate at high speeds of over 1000 km/h. The Future of Hyperloop Study recommended the foundation of an agency responsible for certification on a European level. Furthermore, the study recommended building a test facility that allowed pods to be tested at high speeds in order to guarantee and prove the safety of Hyperloop.
Chapter 14: Future Points of Notice

Main points of notice for future implementation discussed in the Future of Hyperloop Study were divided into two areas. The first includes the barriers to Hyperloop development and is further divided into the two main components that hinder the advancement of Hyperloop, namely:

- **Standardization** - Setting up a standard too soon may constrain the development of innovative concepts.;

- **Financing** - It is unlikely that one single party would finance the construction of the Hyperloop network. Public Private partnerships are likely required. However, it is expected that such networks will eventually extend internationally, and it is difficult to determine the contribution from stakeholders.

The second area concerns the challenges that make Hyperloop less feasible and is divided into nine main components that every transportation regulatory body should be aware of as they comprise both governance and technical aspects. These are, namely:

- **Politics** - Hyperloop systems will likely be inter-jurisdictional; therefore, close communication is required between local governments, national governments and other stakeholders to ensure alignment of objectives. Accessibility and station locations will likely be influenced by policy considerations as well.;

- **High-speed switches** - The most efficient way to connect all stations within a Hyperloop network is to use a highway system with on- and off-ramps to allow pods to either pass or stop at the station. This configuration would require high-speed switches to allow pods to switch on- or off-ramp at high speeds. The technological feasibility of these switches is yet to be proven.;

- **Data Communication** - Decisions still need to be made about whether the data collection for the levitation mechanism will be in-pod or at-infrastructure, the type of photoelectric sensor used to facilitate communication between the moving pod and the tube, as well as what data is presented at the surface of the pod.;

- **Safe Haven Design** - Designing emergency exits in a way that balances safety requirements and costs is a challenge due to the uncertainty of the Hyperloop design and a lack of regulations.;

- **Business Case Towards Implementation** - The first Hyperloop link should create sufficient passenger demand to increase economic feasibility of the link.;

- **Technology Costs Reduction** - Costs for innovative new technologies have not yet been optimized. Reducing cost of levitation and propulsion technologies could greatly reduce the total costs for the Hyperloop infrastructure.;
• **Integration with Current Modes of Transportation** - Spatial constraints make intermodal connection of Hyperloop to other modes of transportation challenging.

• **Crossing Waterways** - Bridge spans and water depths may be too large for a bridge to be feasible. Submerged floating tunnels have been proposed as a possible solution but still require fundamental research and development.; and,

• **Tunnel Boring Machine Speed** - it is estimated that 50% of Hyperloop infrastructure will be built underground. Current Tunnel Boring Machines (TB<) have a boring speed of approximately 15 metres per day in soft soil.

4.5.2 **The Non-Traditional and Emerging Transportation Technology (NETT) Council**

The Non-Traditional and Emerging Transportation Technology (NETT) Council\(^\text{103}\) is an internal deliberative body at the U.S. Department of Transportation (DOT) tasked with identifying and resolving jurisdictional and regulatory gaps that might impede the deployment of new technologies, such as tunnelling, Hyperloop, autonomous vehicles, and other innovations. Since the USDOT consists of eleven operating administrations, each with its own traditional jurisdiction over certain environmental and regulatory approvals, the implementation of new technologies may not fit precisely into the Department’s existing regulatory structure. This could potentially result in a slower pace of transportation innovation in North America in general, and in the United States, in particular.

According to its Charter, the responsibilities of the U.S. Department of Transportation’s NETT Council are to:

A. Identify and resolve jurisdictional and regulatory gaps associated with non-traditional and emerging transportation projects pending before DOT, including with respect to:
   - Safety oversight; Environmental review; and Funding issues.

B. Coordinate the Department’s internal oversight of NETT projects and outside engagement with project stakeholders.

C. Develop and establish department-wide processes, solutions, and best practices for identifying and managing NETT projects.

The NETT provides a government body built to bridge the gap between new technologies (e.g. Hyperloop) and existing governance structure of other transportation modes. This could be a model other authorities might chose to adopt to provide an entity that facilitates inter-relationships between the different levels of government (e.g. federal, provincial, municipal) and that ensures best deployment of technology.

\(^{103}\) [https://www.transportation.gov/nettcouncil](https://www.transportation.gov/nettcouncil)
4.5.3 The Joint Technical Committee (JTC 20) on Hyperloop Systems

The Joint Technical Committee (JTC 20) on Hyperloop Systems\footnote{104} was officially established in February 2020. The Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) announced the launch of a new Joint Technical Committee, CEN/CLC/JTC 20 dedicated to Hyperloop system standardization.

The creation of this committee reflects the effort currently being directed into developing a European standard for Hyperloop, and how it could play a crucial role in achieving a coherent roll-out of Hyperloop as a new tool of mobility.

This joint technical committee will develop common approaches to system components, including vehicle systems, tube infrastructure and communications protocols. The committee will benefit from its ongoing experience of standardizing rail, space and pressure equipment.

The conception of this committee occurred in June 2018 when four private Hyperloop initiatives signed a cooperation agreement in Brussels to work in a coordinated way, together with the institutions, to define common standards and regulations for Hyperloop. The development of common standards, specifications, and approaches by JTC 20 will help mitigate potential challenges to implementation of the Hyperloop technology across the world in general, and in Europe in particular.

4.5.4 European Hyperloop Development Initiative lead by Zeleros, Transpod, Hardt and Hyper Poland

The European Commission is overseeing the European Hyperloop Development Initiative lead by Zeleros, Transpod, Hardt and Hyper Poland\footnote{105}. This consortium of developers are leading the European Hyperloop Development Initiative (project cost estimated at EUR 100M) that aims to develop a framework to support the potentially disruptive European initiative to increase efficiency, availability and sustainability of the current transport network.

The group’s Research and Development (R&D) framework works towards finding common Hyperloop solutions while also supporting medium and real scale test-track development to ensure safety levels are met and infrastructure complexity is minimized. Its final goal is to achieve Hyperloop systems’ scalability for long-distance routes, both in Europe and globally. These initiatives show the opportunities that investment in this emerging technology could present.

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\footnote{104} The Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC): https://www.cencenelec.eu/news/articles/Pages/AR-2020-003.aspx
\footnote{105} https://ec.europa.eu/eipp/desktop/en/projects/project-11397.html
4.5.5 Hyperloop Transportation Technology and Tüv Süd Guidelines

Hyperloop Transportation Technology and Tüv Süd Guidelines\textsuperscript{106} were presented to the European Commission in 2019. In an effort to regulate Hyperloop technology in a safe manner, several European companies requested the European Commission (EC) create a detailed set of testing and development rules. Guidelines were developed in partnership together with Tüv Süd, a transportation inspection company, and Hyperloop TT. These present the first complete set of generic guidelines for design, operation, and certification to the Directorate-General for Mobility and Transport of the European Commission in Brussels.

The two organizations, along with world-leading reinsurance company, Munich Re, revealed that Hyperloop was safe and insurable with the first core safety requirements and insurance frameworks for Hyperloop systems. The latest draft guidelines build on the completion of the core safety requirements and the implementation of certification processes, as well as further development for the construction and operation of Hyperloop systems worldwide. This initiative between an American based company and a European based one holds promise for the transferability of the guidelines that HTT develops; a valuable source of cooperation that could be mirrored in other locations.

\textsuperscript{106} \url{https://venturebeat.com/2019/05/23/european-commission-urged-to-develop-regulations-for-hyperloop-projects/};
Section: ESTIMATES OF CAPITAL AND OPERATING COSTS
5. **Estimates of Capital and Operating Costs**

5.1 **Introduction**

This section assesses the cost in 2020 Canadian $ unless stated otherwise, to design, build, operate, and maintain Hyperloop systems. The cost assessment presents an order-of-magnitude of the overall capital and operating costs for implementing a generic 500 km long, double tube, Hyperloop alignment with two primary stations at each end. The assessment is conducted at a *concept screening* level of detail and accuracy, with no specific alignment or station locations.

AECOM has developed a sophisticated spreadsheet-based model, which uses a top-down approach to assess capital and operating cost estimates. A separate model was developed to scope relevant Hyperloop subsystem configurations and assess costs for propulsion, levitation, guidance, and power transfer with simple assumptions for other more straightforward subsystems (e.g. tube diameter, vehicle mass). This evidence-based approach provides a range of independent system performance calculations.

At the time of writing (March 2020), Hyperloop technology as a viable transportation mode has not been proven or validated, though multiple technology providers continue to develop and refine the concept. Approximately three dozen Hyperloop planning and preliminary feasibility studies have been undertaken throughout the world over the past five years (with the bulk of them in North America), and the few that are publicly available offer little granular detail regarding capital or operating costs\(^\text{107}\). Furthermore, the design and specification of portals and facilities are at most at an early concept level, making the estimation of their operating costs difficult to address. As such, the analysis relies on existing technology assessments, public cost information available for Hyperloop and other relevant projects, and input from Hyperloop technology companies. The cost analysis focuses on the passenger application — information is sparse on freight or a mix of passenger and freight applications. **Appendix H** presents the survey questionnaire specific to the cost analysis.

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\(^{107}\) Publicly available Hyperloop studies include the Great Lakes Hyperloop Feasibility Study (2019), the Preliminary Study on the Implementation of a TransPod Hyperloop Line in Thailand (2019), and the Missouri Blue Ribbon Panel on Hyperloop. The latter is not a feasibility study, but it references the cost estimates from the Missouri Hyperloop Feasibility Study (2019), which is not publicly available as of March 2020.
The cost estimates presented in this section are considered very preliminary given the limitations associated with obtaining detailed information, as well as the proprietary nature of the technologies of the different Hyperloop companies.

In future, should it become necessary for Transport Canada to revisit these cost estimates, it should be done once the Hyperloop technology is further advanced and independent cost investigations are undertaken. This will allow for the development of more reliable cost estimates.

5.2 Capital Cost Assessment

The capital investment is evaluated using two proprietary tools. The first tool models system-specific cost estimates for propulsion, levitation, and power systems for each of the propulsion systems investigated in Section 3 - Hyperloop Concept and Engineering. The second model assesses all other expenditures required for the construction of a Hyperloop corridor, including civil infrastructure, facilities, capsules, professional services, contingencies, etc.

In total, the capital outlay required to build a 500 km elevated double tube guideway, with an average height of approximately six metres, could range between $20 B (baseline) and $32 B (60% contingency factor) depending on the level of contingency considered. For the purpose of this analysis, we apply a contingency factor of 40% to our baseline cost estimates, which translate to $28.2 B in total or $56.4 M per kilometre, excluding property acquisition costs. The analysis assumes the alignment is elevated without any underground tunnelling needs, any major flyover or viaduct, and is all within a dedicated Right of Way.

Table 25 summarizes the total capital cost estimates. Together, the guideway, tubes and switches, and professional services represent half of the total, with relative shares of 43% and 15% of the total, respectively. The costs to build the two stations, the pod depots, and any support facilities amount to $2.73 B or 10% of the total. Hyperloop-specific systems costs, estimated at $3.3 B, represents 12% of the total. Note however, that these cost figures represent an average of the different Hyperloop systems investigated and may thus vary depending on the propulsion technology. The construction costs for the pods, estimated at $650 M, represents 2% of the total. Assumptions, data sources, and results for each cost category are detailed in proceeding sub-sections.

The analysis is performed in real terms and as such, it does not consider the potential impacts of the project schedule, inflation, financing costs, or funding sources. The cost estimate includes unallocated and allocated contingencies adding up to approximately 40%, an appropriate contingency level to carry for ‘Class 5’ estimates, which is applicable to projects such as this, where the degree of definition varies between 0 and 2%.108

Table 25: Capital Cost Estimate Breakdown for a 500-km Generic Hyperloop Corridor in Canada

<table>
<thead>
<tr>
<th>Description</th>
<th>Capital Cost (Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guideway, Tubes &amp; Switches</td>
<td>$12,080</td>
</tr>
<tr>
<td>Stations &amp; Depots</td>
<td>$1,100</td>
</tr>
<tr>
<td>Support Facilities</td>
<td>$1,630</td>
</tr>
<tr>
<td>Sitework</td>
<td>$1,480</td>
</tr>
<tr>
<td>Systems</td>
<td>$3,330</td>
</tr>
<tr>
<td>Vehicles</td>
<td>$650</td>
</tr>
<tr>
<td>ROW &amp; Land Acquisition</td>
<td>N/A</td>
</tr>
<tr>
<td>Professional Services</td>
<td>$4,260</td>
</tr>
<tr>
<td>Unallocated Contingency</td>
<td>$3,670</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$28,200</strong></td>
</tr>
</tbody>
</table>

The cost structure is formatted in a manner that facilitates comparison to other cost estimating structures and formats of high-speed transportation systems nationally and across the world.

The cost structure uses the US Federal Railroad Administration (FRA) Standard Cost Categories (SCC)\(^{109}\), which serves both as a structure and a summary for the capital cost estimate of a Hyperloop system. This format facilitates comparison to other estimates for high-speed transportation systems that have used the SCC format or equivalent in the past and makes it easier to track and control changes over time as the estimate evolves. The SCC format consists of the following 10 categories, with parentheses denoting typical Hyperloop terminology if different:

I Guideway, Tubes and Switches  
II Stations, Stops, & Termini (“Portals and Depots”)  
III Support Facilities  
IV Sitework & Special Conditions  
V Systems  
VI Right of Way (ROW), Land & Existing Improvements  
VII Vehicles (“Capsules” or “Pods”)  
VIII Professional Services  
IX Unallocated Contingency  
X Finance Charges (not evaluated in this study)

The assumptions, data sources, and results for each cost category are explained in detail in the proceeding sub-sections.

5.2.1 Guideway, Tubes and High-Speed Switches

The capital cost to build the guideway, the tubes, and the switches is estimated at $12.08 B.

Guideway – The cost to build the guideway alone amounts to $10 B. The estimate assumes that 20% of the alignment is at-grade using lower height pylons (2 meters) while the remaining 80% is assumed to be elevated on pylons (6 meters).

Elevated structures cost approximately $1.2 M more than at-grade structures on a per kilometre basis. An alignment entirely at-grade would cost approximately $9.6 B compared to $10.2 B for a completely elevated guideway.

The analysis does not account for the cost of bridges and tunnels to allow for comparison with other Hyperloop corridor studies, which use similar assumptions. However, aerial structures and underground tunnels could be necessary for certain applications of the technology in Canada.

Based on costs for similar construction projects in the United States and Canada, at-grade and elevated structures could cost approximately $20 M per route-km to build, whereas aerial structures (high bridges, viaducts) and underground tunnels (twin-bore tunnels) could cost in excess of $175 M per route-km.

These additional costs may have significant implications for the design of a potential alignment or the location of stations.

Geological conditions and the quality of the bedrock would also need to be considered during the design of a guideway. Post-glacial till is typically composed of a mixture of gravel, sand, and silt and is often densely packed and suitable for bearing infrastructure as well as tunnelling operations. However, smaller pockets of other, less-competent bedrock and overburden may require mitigation measures through the alignment design and geotechnical engineering, incurring additional costs.

Tubes – The cost estimate for tube structures relies on information gathered from available Hyperloop studies. The analysis assumes a cost of $4 M per kilometre to build elevated tubes, which amounts to a total of $1.95 B for a 500 km double tube alignment.
High-Speed Switches – The only Hyperloop switching technology demonstrated publicly is the one developed by Hardt (conducted at low speeds and at a reduced scale).

This is implemented through two serial infrastructure-side propulsion / levitation / guidance tracks, which slowly diverge and split into two parallel tracks. Therefore, it is reasonable to assume that for the length of the switch, the cost of the propulsion / levitation / guidance systems should be double. It is also likely that the tube will need to be widened for some or all of the switch length.

It is feasible that this could more than double the cost of the tube for the length of the switch, as it is not simply a matter of putting two tubes next to one another.

Survey responses from Hyperloop companies indicate that switching will be possible at more than half of the maximum operational speed; therefore, the switching speed is assumed to be around 600 km/h. Assuming a tube diameter of, at most, 5 m, a vehicle will need to move at least 5 m laterally to complete a track switch. For passenger comfort reasons, lateral acceleration is expected to be in the range of 0.1 G. This would convert to a minimum switch length of around 750 m.

It is estimated that the additional cost of a track switch would be around $2.6 M. Assuming twenty switches (one per emergency exit) in total, and a 30% contingency, results in a total cost of $67.6 M for switches.

5.2.2 Stations, Depots, and Ancillary Structures

Capital and operating expenditures for Hyperloop stations, pod depots, and maintenance facilities will vary significantly depending on a variety of factors, primarily their size and location. Very little information about the size, equipment, and staging area required to maintain and operate the pods is available at this time.

The analysis assumes the design and construction of two new primary stations at each end of the corridor at a cost in the order of $550 M per station. The cost estimates include the civil, structural, architectural work, a provision for Hyperloop-specific station equipment such as pod bays, chargers, TMS, valves, compressors, etc. and a contingency of 30%. This cost figure assumes that the new termini would be built in dense urban cores.

Capital costs for smaller, interline stations could resemble those of a commuter rail station or an intercity rail station (i.e., VIA Rail), which could range between $25 M and $250 M, depending on size and location\(^\text{110}\).

On the other hand, costs would increase steeply if we were to consider more sophisticated, airport-like facilities or an intermodal hub with architectural landmarks.

For instance, costs to renovate Union Station in downtown Toronto, the largest and busiest transportation hub in the country, are estimated at $830 M\textsuperscript{111}, without considering any additional costs for the specialized equipment that would be required to support the Hyperloop equipment.

Cost variations will depend, notably, on the following:

- New standalone station versus integrated station at an existing transportation hub;
- At-grade or underground stations;
- LEED certification; and,
- Extent and availability of passenger amenities.

Additional factors impacting facility costs include:

- Layout of facilities – spread across an area horizontally or stacked vertically;
- Appropriate capacity and services to accommodate passenger and administrative needs;
- Number of pod loading and unloading areas; and,
- Space to accommodate security screening needs if required.

### 5.2.3 Support Facilities

The support facilities consist of the wayside emergency access points and pressure or vacuum management system. Together, these elements are expected to cost approximately $1.63 B.

Hyperloop companies have indicated that the emergency exits could be spaced approximately every 20 to 25 km, for a total of 20 or 25 exits for a 500 km corridor. However, it is worth noting that current guidance for tunnels states these exits need to be approximately every 760 m as a comparison.

Costs include installation, commissioning and airlocks at every emergency exit. Based on documents provided by TransPod\textsuperscript{112} and other Hyperloop companies, the cost of vacuum pumping infrastructure is estimated at around $2 M per km for a double tube system. This includes the cost of housing the pumps and their control systems, as well as connecting them to power.

\textsuperscript{111} City of Toronto, ‘Union Station Revitalization Project (USRP) – Amendment to the Project Budget and Capital Plan’, Toronto, 2018. Available at: https://www.toronto.ca/legdocs/mmis/2018/ex/bgrd/backgroundfile-111951.pdf

5.2.4 Sitework

Sitework costs are estimated at $1.48 B, which represents approximately 10% of the sum of guideway and facilities costs presented above. The cost breakdown structure for site work is listed below, with the values in parentheses representing the percentage applied to guideway and facilities costs for each item. These assumptions were compiled by the AECOM team using other Hyperloop studies and our extensive experience in planning, designing, and building similar infrastructure projects in North America.

Sitework costs are comprised of the following:

- Demolition, Clearing, Earthwork, Drainage (2% of the total guideway and facilities costs);
- Site Utilities, Utility Relocation (3%);
- Hazardous material, contaminated soil removal/mitigation, groundwater treatments (0.7%);
- Environmental mitigation, e.g. wetlands, historic/archaeologic, parks (0.5%);
- Site structures including retaining walls, sound walls (0.3%);
- Pedestrian/bike access and accommodation, landscaping (0.3%);
- Automobile, bus, van accessways including roads, parking lots (0.3%); and,
- Temporary Facilities and other indirect costs incurred during construction (3%).

Cost variations for site work will depend, notably, on the following:

- Integration with non-transportation development such as a major commercial development or district;
- Extent and availability of parking facilities, including parking structures and accessibility to highways; and,
- Ease of connections to other access modes (active transportation, bus, rail/light rail, air).

5.2.5 Systems

Proprietary parametric models were developed to simulate the performance of different Hyperloop systems and estimate their costs. In essence, these models define the trajectory of a vehicle and design appropriate components for propulsion, levitation/guidance, and power delivery. The individual components are then combined in various ways to represent different Hyperloop system configurations while accounting for any interactions between components.
Figure 24 summarizes the model results for different combinations of propulsion, levitation/guidance, and power delivery systems for the 500 km example double tube hyperloop system. Results range between $1.45 B and $5.72 B depending on the propulsion system. Indeed, the choice of linear motor used for propulsion (i.e., whether the primary elements of the motor are placed on the infrastructure or the vehicle) affects the capital and operating costs of the system, energy consumption, system control strategies, and many other design characteristics.

Infrastructure-side propulsion requires a high-power grid connection, while vehicle-side propulsion requires larger onboard batteries that affect the weight of the vehicles and, therefore, the overall energy consumption of the system. For vehicle-side propulsion and intermittent propulsion, where the primary element of the motor is on the pods, the capital cost is composed of a fixed lump sum for the guideway and an additional cost per pod.

The analysis assumes that 100 pods would be required to operate the 500 km corridor example (refer to Section 5.2.6 for more details). The infrastructure-side propulsion technology is more costly, but the cost would not be sensitive to the number of vehicles in the system. For analysis purposes, a value of $3 B, the average of all six estimates, is used as the point estimate for the propulsion, levitation/guidance and power delivery systems. Costs of $330 M for the central control system are also included in this category. In total, systems are expected to cost approximately $3.33 B, which represents 12% of the total capital costs.

These cost estimates will vary depending on the system’s performance parameters, developers’ design decisions, cost of building blocks (copper wire, sheet metals, permanent magnets, battery cells, power electronics), and the cost of labour. Also, technologies that have not been proven to be functional (i.e. contactless power transfer and axial compressor) are not accounted for in the total. It is believed that axial compressors should have no direct impact on the cost of infrastructure, however, they are likely to have a significant impact on vehicle costs – adding over $1 M to the cost of each vehicle.

Figure 24: Summary of Propulsion, Levitation / Guidance and Power Delivery Costs
The modelling approach is summarized below.

The first step taken in modelling the system costs consists of determining the mechanical power requirements for the Hyperloop system for a given vehicle mass, maximum acceleration rate, and maximum operational speed. For the 500 km, double tube Hyperloop system example, the following characteristics were assumed:

- Vehicle mass: 15,000 kg excluding propulsion, levitation/guidance and energy systems
- Maximum acceleration rate: 1.96 m/s² (0.2 G)
- Maximum operational speed: 277.78 m/s (1000 km/h)
- Operational air gap: 10 mm

As a second step, the unit propulsion blocks’ primary and secondary elements are laid out across the length of the track in various ways to represent different system configurations (vehicle-side, infrastructure-side, intermittent propulsion). The unit propulsion block design assumes a 10 mm operational air gap.

The power and levitation/guidance systems are designed in parallel. The power system design includes batteries (if applicable), inverters, power substations, and power distribution, considering the estimated efficiency of the propulsion system. Where appropriate, the levitation/guidance systems are designed to operate at the same air gap as the propulsion system. Following the example of existing MagLev systems, some elements of propulsion and levitation/guidance can be integrated, which allows the model to estimate the capital costs of propulsion, levitation, and guidance systems together. The model is calibrated to consider the mass of the vehicle using the different subsystems.

5.2.6 Vehicles

Capsule costs are likely to vary greatly depending on their capacity and the configuration of systems responsible for propulsion, levitation / guidance, and power delivery.

For this analysis it was assumed pods have a carrying capacity of between 30 to 60 passengers. Based on the information provided by Hyperloop technology companies and previous studies, a reasonable range for capsule cost is around $3 M to $10 M. Some Hyperloop companies have suggested a more conservative estimate, ranging between $10 M and $75 M, depending on passenger capacity.

Fleet costs for capsules and pods assume the professional services associated with the development of the fleet are included. These costs include professional services, design and manufacturing contractors, warranty, and insurance costs, among others. As discussed in Section 3 – Hyperloop Concept and Engineering, very little information is available on freight pods or combi pods, which, in theory, could accommodate both cargo and passengers.
Survey responses indicate that a 500 km segment would typically require 10 to 15 vehicles per direction. However, to achieve headways (ranging between 18 and 120 seconds) and accommodate loading, unloading and dwell time at stations, more vehicles would be required within the system.

Hence, we estimate that a reasonable number of capsules (pods) for this 500 km, double tube system would be between 85 and 100 pods. For analysis purposes, we assume that purchasing 100 pods would cost approximately $650 M, including contingencies.

5.2.7 Right of Way and Land Acquisition

The cost of any land acquisition for alignment and station Right of Way has not been analyzed in this study. Typically, larger facilities and more urban and central locations incur greater land acquisition costs.

For example, a centrally located rail station, such as Toronto’s Union Station or Montreal’s Gare Centrale may be expected to have a higher capital cost than a station located at, or integrated with, a non-central business district location such as Toronto’s Lester B. Pearson International Airport or Montreal’s Pierre Elliott Trudeau International Airport.

Similar to other transportation facilities, the connectivity and accessibility of the Hyperloop station will be important to its integration into the overall transportation network of an urban area and the surrounding region. Connectivity to other modes of transportation, whether road, rail, or air, ensures ease of access for passenger or freight use.

5.2.8 Professional Services

Professional services, estimated at $4.26M, represent close to 30% of the guideway, stations, support facilities, site work, and systems costs. These assumptions were sourced from the 2010 Transit Cooperative Research Program (TCRP) Report 138 titled “Estimating Soft Costs for Major Public Transportation Fixed Guideway Projects”113.

Professional services include:

- Preliminary Engineering (3% of subtotal costs);
- Final Design (8%);
- Project Management for Design and Construction (3%);
- Construction Administration and Management (7%);
- Professional Liability and Insurances (2%);

• Legal, Permitting, and Other Fees (1%);
• Surveys, Tests, and Inspections (1%); and
• Start-up Costs (1%).

5.2.9 Comparison with Other Hyperloop and High-Speed Rail Capital Costs

The modelling exercise suggests that a 500 km generic Hyperloop corridor in Canada could cost in the order of $28.2 B to design and build, which corresponds to a cost of $56.4 M per kilometre. These results are now compared to cost estimates for other Hyperloop corridors and high-speed rail projects.

Six Hyperloop studies included capital cost estimates, with unit costs ranging between $19 M and $53 M, with an average of $37 M per kilometre, as summarized in Figure 25. The cost estimates presented in the different studies are converted to Canadian currency and adjusted to 2020 dollars. Varying levels of detail and corridor length explain the differences in unit costs.

For example, the least costly estimate, from the Musk Alpha Paper, omits cost items such as site work, systems, professional services, and unallocated contingency, which together represent 40% of our cost estimate. The only other study to have included system costs is the TEMS Great Lakes. It is important to note that none of the previous studies include Right of Way and land acquisition costs.

Our analysis also considers unallocated contingencies representing 13% of the total costs, which other studies do not include. Table 26 identifies the corridor length, the number of stations, and the cost categories covered in each study, which may help explain the major difference observed between the different studies.

Figure 25: Capital Cost Estimates from Previous Hyperloop Corridor Studies (2020 $ M)
Table 26: Capital Cost Estimates from Previous Hyperloop Corridor Studies

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperloop Company</td>
<td>SpaceX</td>
<td>KPMG</td>
<td>VHO</td>
<td>TransPod</td>
<td>TEMS</td>
<td>AECOM</td>
</tr>
<tr>
<td>Total Cost ($M)</td>
<td>$9,750</td>
<td>$24,700</td>
<td>$6,240</td>
<td>$10,300</td>
<td>$33,020</td>
<td>$28,200</td>
</tr>
<tr>
<td>No. of Stations</td>
<td>2</td>
<td>11</td>
<td>4</td>
<td>not included</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>563</td>
<td>500</td>
<td>150</td>
<td>350</td>
<td>754</td>
<td>500</td>
</tr>
<tr>
<td>Total Cost ($M) per km</td>
<td>$17.3</td>
<td>$49.4</td>
<td>$41.6</td>
<td>$36.3</td>
<td>$43.8</td>
<td>$56.4</td>
</tr>
</tbody>
</table>

**2020 Cost ($M) per km**

| Double Tube (two-way) | ✓ | ✓ | ? | ✓ | ✓ | ✓ |
| Tunnel | ✓ | ✓ | x | x | ✓ | x |

**Tunnel Percentage**

| Guideway | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Stations & Depots | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Support Facilities | ✓ | ✓ | ? | x | ✓ | ✓ |
| Sitework | x | ? | ? | ✓ | ✓ | ✓ |
| Systems | x | ? | ? | x | ✓ | ✓ |
| ROW and Land | - | x | x | x | ✓ | ✓ |
| Vehicles | ✓ | ✓ | ? | x | ✓ | ✓ |
| Contingency | - | ✓ | ? | ✓ (16%) | ✓ (30%) | ✓ (30%) |
| Professional Services | x | ✓ | ? | ✓ (10% CM only | ✓ (28%) | ✓ (15%) |
| Unallocated Contingency | x | ? | ? | x | x | ✓ (13%) |
| Finance Charges | x | x | x | ✓ (8%) | ✓ | x |


[^115]: [https://hyperloop-one.com/blog/we-ran-the-numbers-on-euro-hyperloop](https://hyperloop-one.com/blog/we-ran-the-numbers-on-euro-hyperloop)


[^118]: [https://www.glhyperloopoutreach.com/feasibility-study](https://www.glhyperloopoutreach.com/feasibility-study)
As part of the analysis the developed capital cost estimates have been compared to three recently completed high-speed rail (HSR) corridor studies (see Table 27).

In 2004, the Van Horn Institute completed a study119 exploring a high-speed rail link between Calgary and Edmonton, Alberta.

The study includes cost estimates for three scenarios (use of existing tracks, greenfield alignment with diesel trains and greenfield alignment with electric trains). Electric trains considered for this study are expected to reach 320 km/h. Capital costs are estimated at approximately $18 M per km, including land acquisition costs for the Right of Way. However, the analysis assumes the corridor would use existing stations, resulting in an allocation of only $40 M for stations and parking facilities.

In 2016, the Ontario Ministry of Transportation commissioned a preliminary business case for a high-speed rail corridor connecting Toronto to Windsor, Ontario. The best performing scenario (B) extends over 365 km and is designed to leverage existing corridors where possible and achieve a maximum speed of 250 km/h.

The capital cost estimates for Scenario B are in excess of $56 M per km, including land acquisition costs for the required Right of Way and a 66% contingency factor. The report recommends further analysis and engineering works to increase cost accuracy and revise the economic performance of the project (benefit-cost ratio of 0.70).

In 2017, the Washington State Department of Transportation completed a high-speed rail study, which assessed the feasibility of connecting Portland, Oregon, Seattle, Washington and Vancouver, British Columbia, a 500 km-long corridor, which is also a cross-border, multi-state endeavour120.

The Portland-Seattle-Vancouver Ultra HS, “Cascadia” study provides a rather broad range for the potential cost using two different technologies, high-speed rail and magnetic levitation (MagLev), through multiple alignment options that range from 3 to 7 stations.

The high-speed rail and MagLev systems are designed to achieve speeds of 350 km/h and 435 km/h, respectively. The capital cost estimate ranges between $48 M to $84 M per km depending on the corridor and the technology.

A high percentage of tunnelling was included as a capital cost input to the CONNECT model. The report suggests that more detailed analyses of alignments and technology could reduce costs by at least 25%.

120 https://www.wsdot.wa.gov/publications/fulltext/LegReports/17-19/UltraHighSpeedGroundTransportation_FINAL.pdf
Table 27: Cost Estimates for Selected Canadian High-Speed Rail Studies

<table>
<thead>
<tr>
<th>Consultant</th>
<th>Calgary-Edmonton</th>
<th>Toronto-Windsor</th>
<th>Portland-Vancouver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Van Horn Institute</td>
<td>Steers (Formally SDG)</td>
<td>CH2M Hill</td>
</tr>
<tr>
<td>Date</td>
<td>Dec 2013 (update)</td>
<td>Nov 2016</td>
<td>Feb 2018</td>
</tr>
<tr>
<td>Total Cost ($M)</td>
<td>$5,186</td>
<td>$20,940</td>
<td>$24,000 to $42,000</td>
</tr>
<tr>
<td>Technology</td>
<td>320 km/h Electric HSR</td>
<td>250 km/h Electric HSR</td>
<td>350 km/h HSR; 435 km/h MagLev</td>
</tr>
<tr>
<td>No. of Stations</td>
<td>5</td>
<td>7</td>
<td>3 to 7</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>310</td>
<td>376</td>
<td>500</td>
</tr>
<tr>
<td>Total Cost ($M) per km</td>
<td>$16.7</td>
<td>$55.6</td>
<td>$48M to $84M</td>
</tr>
</tbody>
</table>

5.3 Operations and Maintenance (O&M) Costs

In general, operating costs for a Hyperloop system would comprise of two main components: variable and fixed operating costs. At the most basic level, variable costs include labour, energy, and fleet and equipment maintenance.

Fixed operating costs would include infrastructure maintenance, portals and facilities maintenance, control and command, leasing (if applicable), and insurances. Fixed operating costs not assessed or estimated in this high-level analysis include general administration and executive management, and commercial costs (marketing, distribution, credit card sales).

The following sub section provides a discussion of the different types of operating costs and, where possible, some high-level recommendations on estimation assumptions or methodology for those types of costs. To date, very few studies have provided O&M cost estimates for a Hyperloop corridor.

Available studies rely on a cost-recovery approach in which O&M costs are estimated as a percentage of anticipated fare revenue per passenger-km. A demand forecast and fare revenue analysis is outside the scope of this study.

Hence, at this stage, we do not have the necessary input to provide robust O&M cost estimates for a generic 500 km alignment in Canada. It should also be noted that we could not locate any study assessing operating costs associated with freight movement on a Hyperloop alignment.
5.3.1 Portals and Facilities

Operating costs for the Hyperloop portal and facilities could include personnel, utilities, leasing costs (if applicable), and insurances. Additional recurring annual costs would include maintenance of vehicles, tools, and IT systems.

Portal personnel would include portal managers, ticket agents (if applicable), passenger assistance representatives, facility maintenance managers and staff and security. Further employees could include pod maintenance and cleaning crews if that is to be undertaken at the station. Station and facility personnel headcount would depend on the number of portals and facilities and network ridership.

Utility costs at the portals would be the largest expense and would comprise electricity, water and sewage, and potentially natural gas for co-gen powered heating and cooling systems.

Hyperloop portals could be standalone facilities or incorporated into existing multimodal transportation hubs such as central stations or airports. Their size could vary considerably depending on whether they were a terminus station or intermediary stop, the estimated ridership for that portal, and whether parts of the Hyperloop fleet would be stored on-site.

The costs to maintain the facilities, including the portal, would include the operating, upkeep, and maintenance of the Hyperloop portals (stations), maintenance facilities, storage yards, power stations, and other dedicated facilities. As none of these facilities have been built and details on their design and configuration are still at a very early stage, the most pragmatic way to estimate their operating costs would be to examine benchmark operating costs from existing traditional rail stations and facilities in order to derive an annual cost per square metre. However, information on the operation and maintenance of individual major transportation facilities is not generally publicly available, with information on the individual operating costs aggregated in a single line item in the transportation owner/operator’s annual reports.

Current operating costs for maintenance and repair, utilities, and janitorial services for large format commercial buildings is approximately $165 per square metre per annum\(^{121}\).

Given that transit stations generally have a lower density of built space than commercial buildings, an annual operating cost of $100 per square metre per year would perhaps be a more appropriate estimate.

\(^{121}\) BOMA Commercial Building Costs Benchmarks, 2019
5.3.2 Labour

Very little published information exists relating to the labour requirement of operating a Hyperloop system. Most Hyperloop technology providers predict that their proposed systems will be largely automated, with driverless pods, mobile ticket purchase, and maintenance pods that may be unmanned. Of course, even a largely automated network would require a significant workforce for administration, operations, maintenance, and station staff, though no estimations have been made at this time as to the size or configuration of such a workforce.

5.3.3 Power

Like high-speed rail, Hyperloop technology would be powered by electricity. Hyperloop technologists have publicized this as one of Hyperloop’s key attributes as it would represent a high-speed alternative to other fossil fuel-powered modes such as road, air, and train travel.

Some technology providers have speculated that their entire network could be powered by solar energy or a mix of other renewable energy sources (hydro, wind).

This is compelling in theory, but a thorough search for existing information on the energy requirements for operating a Hyperloop network yielded nothing published on this subject. A potential network powered entirely by solar power would require a significant capital outlay from the network’s developer and could be problematic in some climates where seasonality can make direct sunlight scarce for sustained periods.

Traction power requirements would depend on the technology used, the network’s location and terrain, and the type of power generation utilized. For instance, in Quebec, where the majority of electricity is produced using hydroelectricity, energy costs for large industrial users are approximately half of what analogous users in neighbouring Ontario pay\(^{122}\).

5.3.4 Maintenance of Infrastructure

Maintenance costs would include the inspections, scheduled and unscheduled repairs of the Hyperloop tube, track, tunnels, viaducts, power systems, and all other non-portal/facilities/fleet infrastructure. This maintenance does not include asset renewal, which is included in the system’s lifecycle capital costs.

Much of this infrastructure – particularly the major civil works that will make up the majority of the system’s capital costs – would be assumed to have asset lives in excess of 50–75 years.

Maintenance would be relatively minimal in the short term and largely be comprised of inspections and scheduled maintenance. Components with a shorter expected lifespan – track and power systems – would have higher annual maintenance costs.

\(^{122}\) Statistics Canada, 2019.
A conservative operating cost for maintaining the Hyperloop system’s infrastructure is estimated as follows:

- 0.5% of the capital costs per annum for major civil works;
- 3% of capital costs per annum for track and power systems; and,
- 2% per annum for all other infrastructure.

### 5.3.5 Operating Cost from Previous Hyperloop and HSR Studies

The only Hyperloop operating cost estimates available in the public domain from a relatively granular feasibility study are those from the 2019 Great Lakes Hyperloop Feasibility Study\(^\text{123}\). This study estimates total operating costs at $0.16 per revenue (passenger) kilometre.

This figure is approximate to assumptions on operating costs that AECOM has developed and used in recent years with other Hyperloop technology providers, though within the context of utilizing a passenger pod with a significantly lower capacity than assumed in the Great Lakes Hyperloop Feasibility Study\(^\text{124,125}\). An overview of the breakdown of operating costs from the Great Lakes study, in US 2018$, is shown below in Figure 26.

Previous Hyperloop studies carried out at a more conceptual level have also attempted to estimate operating costs, albeit at a far coarser level of assessment. An example, shown in Figure 27: is the estimated breakdown of operating costs in the 2017 Netherlands Hyperloop study, carried out by ARUP.

While not directly relevant to the estimation of Hyperloop operating costs, recent studies into the development of high-speed rail and MagLev in North America have estimated operating costs for the different types of high-speed technology. An example of the estimated operating costs (in $USD) from the 2019 Cascadia High-Speed Rail Study, carried out by the Washington State Department of Transportation is shown in Table 28.

\(^{123}\) The draft version of this study can be found at [https://www.glhyperloopoutreach.com/feasibility-study](https://www.glhyperloopoutreach.com/feasibility-study). It is noted that this analysis offers very little insight as to how operating costs – or operating revenue, for that matter – for this potential alignment were estimated.

\(^{124}\) The technology provider which partnered on the Great Lakes Study, Hyperloop Transportation Technologies, assumes a pod capable of carrying 50 people. Their operating cost estimate is based on a pod revenue mile operating cost of $8.05. It is noted that other Hyperloop technology providers have developed concepts for pods with a maximum occupancy of 30, and a pod revenue mile operating cost estimation just below $5.

\(^{125}\) The range of operating costs that AECOM has been given by, or developed in concert with, Hyperloop technology providers is $0.13 to $0.40.
Figure 26: Estimated Operating Costs from the Great Lakes Hyperloop Study, US 2018 $ M
Source: TEMS

Figure 27: Relative Commercial Operating Costs, Hyperloop in the Netherlands (2017)
Source: ARUP, BCI, TNO, VINU (2017)
Table 28: Estimated Operating Costs by Corridor and High-Speed Technology, Cascadia HSR

<table>
<thead>
<tr>
<th>Concept Corridor</th>
<th>Concept Corridor 2</th>
<th>Concept Corridor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSR</td>
<td>MagLev</td>
</tr>
<tr>
<td>1A Seven Stations</td>
<td>O&amp;M Cost Recovery Ratio</td>
<td>0.62 - 0.72</td>
</tr>
<tr>
<td></td>
<td>Total Annual O&amp;M per Passenger Mile</td>
<td>$0.78 - 0.76</td>
</tr>
<tr>
<td></td>
<td>Revenue per Passenger Mile</td>
<td>$0.51 - 0.51</td>
</tr>
<tr>
<td>Standalone Primary Corridor (Portland to Vancouver)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O&amp;M Cost Recovery Ratio</td>
<td>0.50 - 0.62</td>
</tr>
<tr>
<td></td>
<td>Total Annual O&amp;M per Passenger Mile</td>
<td>$0.82 - 0.75</td>
</tr>
<tr>
<td></td>
<td>Revenue per Passenger Mile</td>
<td>$0.45 - 0.43</td>
</tr>
<tr>
<td>Full Network (Primary + Connecting East-West Corridor)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note that this study does include some analysis of Hyperloop, but ultimately focuses on MagLev and HSR given the technology has been validated and there are existing benchmarks from which to draw data.

Source: WSDOT

5.4 Summary of Capital and Operating Costs

The section has considered both the capital and operating costs of Hyperloop. In developing the capital costs, a generic 500 km route was used to help cost the various components.

The analysis of the capital cost shows that the estimated cost per km is $56.4 M, which is substantially higher than the Alpha paper estimate of $19 M per km. This trend of rising costs is demonstrated by the other considered studies which show a general trend of rising costs. This is not a surprise, given the growing complexity of the system demonstrated in the Hyperloop Concept and Engineering section.

It is also important to note that the level of design uncertainty of several key components means that accurately costing the infrastructure is still difficult. This leads to the conclusion that the actual capital cost per km is still likely to change between this estimate and a real-world deployment.
The latest estimate for the capital cost of Hyperloop means that it is no longer appropriate to consider it price competitive with high-speed rail projects.

This marks an important consideration given that the original premise for the concept was founded on the idea of a ‘better’ and ‘cheaper’ alternative to high-speed rail. MagLev is still in the early phases of deployment with a limited number of routes having been implemented. However, at present the capital cost for Hyperloop appears to still be significantly lower than MagLev trains.

The assessment of operating costs has proven to be much more challenging. With so little information about variable costs per trip it is very difficult to know what ticket prices will be. Furthermore, the role journey times savings will play in demand will be a crucial factor in pricing. With such a large gap between current and predicted operating speeds the savings are also subject to significant uncertainty.

Given these uncertainties it is difficult to know what financial operating model an operator or investor might use for a Hyperloop route.
Section: CONCLUSION
6. Conclusion

6.1 Study Overview

This study aims to undertake a holistic assessment of the viability and readiness of the rapidly evolving emergent technology referred to as “Hyperloop”, for high-speed passenger and freight transportation in the Canadian context. A central objective has been to better understand, examine and determine, in the general sense, whether safe, large-scale application of this technology in Canada can be delivered with comparable or lower lifecycle cost to existing transportation modes such as high-speed rail and MagLev.

Using a combination of industry insight, available material, developer input, and transportation consultant expertise, the study has provided:

- a review of the publicly available literature on Hyperloop (as of March 2020);
- a review and assessment of the major engineering components of the Hyperloop system;
- an objective overview of potential risks and hazards associated with the system as they pertain to regulating bodies;
- and an initial/early look at the estimated capital and operating costs of a hypothetical system through a financial/economic lens.

Figure 28, on the proceeding page provides this holistic overview of the study, the primary components of the system, assessment findings, and areas for further development and consideration.

6.2 Assessment

Hyperloop as a technology has only received widespread public attention since 2013, when Elon Musk published his white paper on the subject. The theory of vacuum-based transportation was first developed in the early twentieth century with the realization that removing the air around a train would allow acceleration with less energy expenditure. Since then, the concept of vac-trains has been posited by many different engineers, but no scaled design has ever been commercially pursued.

A defining feature of the model Musk proposed is a low pressure rather than zero pressure environment, which he claimed was more achievable in a commercial setting. He also proposed that capsules should not run on tracks, as this would create too much friction. Instead, they would float on cushions of air (although subsequently, the use of magnetic levitation has developed into the preferred approach). Since the Alpha paper publication, many academic and commercial developers have sought to further refine the concept and progress it to the level of a commercially viable transportation mode.
The Hyperloop Technology Feasibility Study

**ACCELERATION**

- **0.5% of capital cost** / year for major civil works

**SYSTEMS**

- **Breakdown of the communication system components**
- **Infrastructure**
  - Physical infrastructure: “ceilings”, floor, and walls
  - Mechanical systems: HVAC, electrical, and plumbing systems
  - Communication systems: fiber optic, cable, and wireless systems

**ACCELERATION SECTION**

- **ACCELERATION**
  - **600 km/h**
  - **170 m/s**

**SAFETY ASSESSMENT**

- **35%**
  - Vehicles
  - Infrastructure

**BENEFITS OF THE HYPERLOOP**

- **Significant potential for travel time savings**
- **Efficient than that of railways and roads**
- **Much-reduced speed due to mechanical complexity**
- **High-Speed Switching**
- **Remote locations with economic centers**
- **Underserved and rural areas**

**RESEARCH AND DEVELOPMENT CONSIDERATION**

- **Consideration for loading facilities and equipment will be required**
- **Sizing, design and accommodation of different freight requirements presently unknown**
- **High-speed switching remains an unproven concept**
- **High-speed switching exists in current rail/maglev systems, but at track-switching speeds**
- **High-speed switching is needed to provide a continuous travel experience**

**OPERATIONS AND MAINTENANCE COSTS**

- **Innovations and maintenance of new technologies will be essential**
- **Continuous maintenance and monitoring of critical systems**
- **High-speed switching will require new maintenance and monitoring**

**TECHNOLOGY RISK MITIGATION ASSESSMENT**

- **A reassessment of the current state of various engineering components of the hyperloop system was conducted**
- **Assessment of the level of readiness of Hyperloop technology**
- **Identification of key technology readiness levels**
- **Technology Readiness Levels**
  - **1**: Early stage of development
  - **2**: Basic component development
  - **3**: Proof of concept
  - **4**: Demonstration
  - **5**: System prototype
  - **6**: Commercial demonstration
  - **7**: Commercial production

**CONCEPT AS A FREIGHT TRANSPORTATION MODE**

- **Freight Infrastructure**
- **Freight Competition**
- **Specialized freight transportation system**
- **Cost-effective and efficient freight transportation**

**ECONOMICS**

- **Costs to build the guideway, the tubes and the switches**
- **Could cost in the range of $20 – 45 M/km**
- **0.5% of capital cost / year for major civil works**

**TRACK SWITCHING**

- **An individual / lane / channel based between train lanes**
- **Minimum speeds required to be incurred in the track design**
- **Significant travel time savings**

**TRACK MAPPING CONSIDERATIONS**

- **High-speed switching is needed to provide a continuous travel experience**
- **Continuous maintenance and monitoring of critical systems**
- **High-speed switching will require new maintenance and monitoring**

**SYSTEMS, SITES AND LAND STRUCTURES**

- **Consideration for loading facilities and equipment will be required**
- **Sizing, design and accommodation of different freight requirements presently unknown**
- **High-speed switching remains an unproven concept**
- **High-speed switching exists in current rail/maglev systems, but at track-switching speeds**
- **High-speed switching is needed to provide a continuous travel experience**

**SUPPORT FACILITIES**

- **Vacuum pumping stations**
- **Power substations**
- **Stations and terminals**
- **Security**
- **Emergency evacuation systems**
- **Healthcare facilities**

**HIGHLIGHTS**

- **Significant potential for travel time savings**
- **Efficient than that of railways and roads**
- **Much-reduced speed due to mechanical complexity**

**INTERNATIONAL REGULATIONS - EU**

- **EC Certification**
- **Safety and ensuring passenger and freight security**
- **Regulatory bodies**

**INTERNATIONAL REGULATIONS - USA**

- **FCC Certification**
- **Regulatory bodies**
- **Safety and ensuring passenger and freight security**

**SUPPORT FACILITIES**

- **Vacuum pumping stations**
- **Power substations**
- **Stations and terminals**
- **Security**
- **Emergency evacuation systems**
- **Healthcare facilities**

**CONCLUSIONS**

- **The Hyperloop represents a significant technological advancement**
- **A new transportation system**
- **A potential game-changer for the global transportation industry**

**Additional Consideration**

- **Travel time savings**
- **Efficient than that of railways and roads**
- **Reduced speed due to mechanical complexity**

**REFERENCES**

- **REFERENCES**
- **For Further Reading**
- **For Further Reading**
- **For Further Reading**
The concept of Hyperloop is barely seven years old and no more than a few kilometres of full-scale track exist (and these are solely for testing purposes), yet Hyperloop is already being dubbed the fifth transportation mode.

Perhaps because of the media focus on Musk, the technology is gaining global interest and numerous regional and national public agencies are exploring the application of Hyperloop for different transportation corridors. With forecast maximum speeds of up to 1200km/h, it has the potential to change travel and transportation as we know it. The existing publicly available literature on Hyperloop is meager, focusing mostly on the anticipated benefits of its application in particular corridors. Public literature on the technological components and design of the various pods and systems is similarly sparse, with advances kept secret as developers seek to gain a competitive advantage.

Only a handful of reports describe the broader concept of Hyperloop and how it could impact the existing transportation hierarchy, while even fewer explore design regulations or hazard assessments. Where Hyperloop literature does provide some reassurance, is in the credentials of the authors and editors of some of the more impartial work. Among agencies who have put their name to technical reports on Hyperloop are the National Aeronautics and Space Administration (NASA), the Dutch Ministry of Infrastructure and Environment, and Delft University in Holland. The interest of such agencies lends further credibility to the claim that this is a new form of transportation worthy of the attention of transportation agencies around the world.

To date, most of these reports highlight the same series of presently unanswered questions, as noted below. Many also acknowledge that several of the system’s proposed components still require further design and testing to be realized.

- What are the core components of a Hyperloop system?
- What technical areas and aspects of the system remain unresolved?
- What is Hyperloop’s target demographic?
- How have hazards and risks been identified and mitigated?
- What design guidance and regulations exist?
- What will it cost to build and operate?
- How close is the system to commercial implementation?
- What are the biggest challenges for Hyperloop to address?

These are pertinent questions requiring consideration and answers from the Hyperloop technology companies and other interested parties if Hyperloop is to gain credibility as a feasible transportation mode. Currently, much of the current investment and focus continues to be on the refinement of certain technical design of system components.
Hyperloop technology developers have put significant effort into the development of their vehicles (also called capsules or pods) as they look to address propulsion, guidance, communication and operating requirements. With six established Hyperloop companies and new ones joining the pursuit, various approaches are being applied to resolving different technical challenges.

The original concept proposed that pods would ‘float’ in the tubes on an air cushion generated by compressing the air ahead of the capsule and pushing it out underneath the pod to generate levitation. As the concept has been refined, many of the Hyperloop designers are moving towards the use of magnetic levitation (similar to the approach used by MagLev systems in Japan and China) to create lift. Magnetic levitation offers a more stable levitation than the air cushion concept and also provides a guideway for the pods to follow. Pod design differences are not limited to the propulsion and levitation systems. One of the current debates surrounds power supply and whether it should be infrastructure-based or housed within the pods. There are benefits to both approaches but concerns remain over the weight impact of a battery that could supply sufficient power for commercially viable journeys.

The current testing tracks for Hyperloop are, at most, a few kilometres and in no way resemble the sleek, elevated, transparent designs depicted in many promotional articles. The infrastructure for Hyperloop will consist of tubes, likely to be five metres in diameter that will be vacuum pumped to maintain a low-pressure environment. If the tubes are to be as minimalist as first envisioned, the capsules will need to contain all the levitation, guidance and communication systems. However, as already discussed, a number of these systems are being shifted to the infrastructure. With several developers proposing the use of magnetic levitation and guideways, the use of active versus passive levitation and whether to mount the guideway on the top, bottom, or side of the tubes continue to be hotly debated.

Less thought is being given to high-speed switching and tube portals, two elements that still require considerable design refinements. Magnetic or air cushion high-speed switching is a new concept to transportation, with existing systems using mechanical switching, which is most commonly conducted at reduced speeds. High-speed switches are integral to the Hyperloop concept.

Equally, the capacity at terminals will also be impacted if tubes cannot diverge. Envisaged pod capacity varies significantly (ranging from 20 – 80 passengers), however, in all cases, the Hyperloop developers believe a large number of pods will depart and arrive every hour. To achieve this level of throughput, multiple portals providing an interchange from the low-pressure environment to normal conditions will be needed. Similar to the high-speed switches, very little is known about how these portals will work. Table 29 summarises the results of the technology readiness assessment conducted on the various Hyperloop technology components. It indicates a significant number of components remain in the early stages of testing, and a few still exist only as conceptual designs.
Table 29: Estimated Operating Costs by Corridor and High-Speed Technology, Cascadia HSR

<table>
<thead>
<tr>
<th>Major Technology Elements</th>
<th>Technology Readiness Level</th>
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<tr>
<td>Infrastructure</td>
<td>5</td>
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<tr>
<td>Vacuum and Power Stations</td>
<td>7</td>
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<td>Propulsion and Power Delivery</td>
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<td>Axial compressor</td>
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<td>Vehicle-side linear motor</td>
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<tr>
<td>Infrastructure-side linear motor</td>
<td>7</td>
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<td>Levitation and Guidance</td>
<td>7</td>
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</table>

As a cutting-edge technology, many of the proposed system elements will be technologically advanced. The idea that the mode will be highly automated is often cited as an example, however, such a scheme will be heavily reliant on communications systems. With routes potentially spanning hundreds of kilometres, it will be a significant challenge to ensure a continuous and reliable signal across the entire network. The estimated travel speeds of up to 1200km/h represent a value that current wireless networks have yet to address. As highlighted in the risk assessment, some of the most significant safety concerns revolve around communications. There are still many communication challenges to be addressed before the system could operate with the small headways envisaged and split-second timing needed.

Hyperloop is intended to offer a new form of travel for both passengers and freight with fast and price competitive transportation links. With forecast top speeds between 1,000-1,200 km/h, this primarily ground-based transportation mode has the potential to change inter-city and longer distance travel. Despite the potential for significant journey time savings compared with other established modes, Hyperloop is targeted at a particular niche demographic for whom it will hold the greatest appeal. Considered to be a hybrid of rail and air travel, incorporating the best of both modes, it is still constrained by the need to operate on its own infrastructure, thus requiring a significant level of demand to make construction feasible for any particular corridor. These conflicting limitations, among other factors, are why Hyperloop is not seen as a significant competitor to automobiles.

In addition to proposed significant journey-time savings compared with current high-speed trains and reduced time spent preparing for arrival and departure in comparison to air travel, Hyperloop is also being promoted as a ‘green’ alternative to short-haul flights and diesel trains, aiming to attract the growing number of trips where environmental emissions are a factor in mode choice. Several studies have produced ambitious projections about a modal shift in certain existing corridors, although approximate numbers cannot be determined until the technology has been further developed and the pricing better understood.

126 Using publicly available information only. There is currently no information confirming the use of vehicle-side propulsion in any Hyperloop testing facility. We note that the TRL could be revised to Level 6 if there is confirmation that such a technology has been tested at any existing test facility.
Despite this, the emerging market for Hyperloop is focused around inter-city travel, with distances varying from a couple of hundred to as much as fifteen thousand kilometres. The primary aim of such networks is to attract business commuters who might otherwise take air or rail, although it is expected that other travellers will also utilize the new mode. Equally, some of the shorter routes with expected journey times below 30 minutes could prove attractive to those facing commute times greater than that from existing urban peripherals.

Understanding the type of passenger who will use Hyperloop is difficult given the uncertainty over travel time savings, fare levels, hourly capacity, and other transportation attributes. Realization of the maximum proposed speeds has the potential to attract travellers from other modes but if, as some predict, the actual top speeds end up being significantly lower, the shift could be appreciably less, which might hamper confidence and investment in new corridors.

The opportunities for freight are still unknown. Hyperloop companies have discussed the potential for movement of time-sensitive freight, and for freight transportation during off-peak hours. However, until the real and more robust costs of the system are understood, it is difficult to predict what types of freight will find Hyperloop advantageous. While most conceptual pod interiors have been developed for passengers, several companies have discussed how pods could be used for freight containers. Similar to the aviation industry, Hyperloop will most likely require custom freight containers for use with the pods.

There is even less understanding of what Hyperloop terminals will look like or where they will be located. Although there is wide agreement that inter-city commuters will prefer accessible downtown locations, the security, screening and ancillary services that a terminal will need to provide are not yet clearly defined. This makes understanding the potential footprint and size of the terminal hard to determine and raises questions over its ability to integrate within the downtown fabric. Where a freight service is envisaged, a downtown location is unlikely to be logistically desirable; a suburban location or one neighbouring a highway would be much more attractive.

The risks and hazards associated with Hyperloop are not yet fully realized. Operating in a low-pressure environment represents a significant risk that is compounded by the effects of very high travel speeds on capsule and infrastructure integrity, not to mention the effects on the human body.

This study conducted both a Preliminary Hazard and Threats and Vulnerability Assessment to begin classifying the various hazards that Hyperloop presents and where intervention from governing agencies might help mitigate these risks. Cutting edge concepts aside, many of Hyperloop’s components are not new. The reality of travel in lower friction environments has existed for years in air travel and the technology to maintain a comfortable pressure for human passengers is well established. The known risks with existing technology are relatively well understood but a different application could cause unanticipated hazards to emerge. Although vacuum pump technology is well advanced, the wide application of such pumps, across multiple locations spanning hundreds of kilometers along a Hyperloop system, present new hazards for consideration.
Assessment of the risks and hazards affecting Hyperloop can only proceed in lockstep with the progression of the Hyperloop technology. For existing elements, this can be performed at a fairly detailed level, but new Hyperloop technology components such as high-speed switches and tube portals will be entirely novel. The risks associated with these will emerge and evolve as they are further developed, presenting challenges for regulators who will need to consider their involvement in the development and operation of the technology. Ideally, this invites collaborative roles for Hyperloop technology developers and potential government regulatory bodies to direct the evolving design parameters for the technology.

As Canada considers how best to manage the development of Hyperloop, limited global information is available regarding the steps and directions that are needed to begin formulating a regulatory regime. Current agencies grappling with this issue include the European Commission, which is overseeing a joint public-private partnership with several Hyperloop developers aiming to provide appropriate guidance on safety and system testing, as well as agencies in the U.S.A and Holland examining what can be done to develop Hyperloop networks and ensure interoperability between developers. These initiatives are in their early stages and, to date (March 2020), have produced little publicly available information.

As Hyperloop technology and its concomitant regulations continuously change in light of testing and new information, there follows a repercussive effect on cost considerations. Originally conceived to offer a low-cost alternative to high-speed rail, the complexity of the system has increased in tandem with technology development. The switch from the ‘air cushion’ concept to magnetic levitation has meant an increase in infrastructure requirements within the tube, pushing up the capital cost per metre. Although the terminal design is not yet known, many experts believe security procedures will require pre-boarding screening, driving up terminal costs significantly. As these various considerations continue to be fleshed out, the complexities of the design are increasing, driving up capital costs. AECOM priced a theoretical route and found that the cost per kilometre was north of $56M without land acquisition factored in; significantly higher than the original concept predicted (circa $19M) and reflective of the growing technical and design complexities the system is encountering.

Current Hyperloop developers have indicated they do not intend to build and operate the routes themselves and would rather license the technology to operators. On the understanding that private investment will be required to develop these routes, rising capital costs will impact the returns for investors and could drive up ticket prices. One of the selling points of the original concept was that it would operate on solar power, thus being energy-neutral and reducing system emissions. Although still in the testing phases, it is interesting to note that none of the current facilities have installed solar power on the tube infrastructure and it is not known if this will be done on any developed route.

A range of studies for different corridors have been published and each has predicted different capital and operational costs, making potential ticket prices hard to determine. With the technology in a state of ongoing development, it is challenging to understand what operational costs might look like. For example, they will vary significantly based on whether onboard batteries are used versus infrastructure-side power.
Such differences in approach are reflected in the current cost range for capsules, from $3 M - $10 M depending on the developer and technical approach. As capital costs continue to rise, the comparable advantages over other modes lessen. One of the Hyperloop system selling points was a significantly lower per kilometre cost than high-speed rail and MagLev technologies. Rising costs mean this competitive edge is diminished, with many proposed corridors now likely to cost less per km for high-speed rail and in some cases MagLev, than a Hyperloop alternative. For Hyperloop to be a preferred option for implementation in a particular corridor, careful design and costing decisions will be needed to maintain a cost advantage over competing modes.

6.3 Summary

AECOM has reviewed the engineering, safety, and cost considerations for Hyperloop and has provided an independent assessment. The assessment has considered a range of information provided from public sources, technology developers and industry experts. In light of the study, the rate at which the technology is evolving is clearly apparent. That significant effort and investment is going into this development reflect the belief that a viable solution is achievable. However, despite the progress to date, there remain several challenges to overcome:

- **Anticipated Speed** – The proposed maximum speed will be between 1,000 km/h and 1,200 km/h (depending on the developer). However, such speeds have yet to be demonstrated in any real-world environment. Speed being one of the main selling points of the system, a failure to operate at anything close to these will sufficiently diminish the viability of the mode in many scenarios.

- **Environmental Impacts** – As a new technology, the hope was that this could be close to a zero-emission mode. However, if the energy supply must be drawn from the main grid this will harm the environmentally friendly image. Equally, issues regarding noise, vibration and visual impacts are yet to be fully understood and could also tarnish the clean, green image.

- **Technical Components** – Several technologies, such as high-speed non-mechanical switching, terminal portals and Hyperloop compatible communication systems, remain unproven. These elements will need to be developed and validated at speed before the system can be considered fully feasible.

- **Capital Costs** – The estimated capital costs for developing a system will need to be carefully managed to remain competitive with alternatives. This will prove challenging, with costs already rising and the additional requirements for regulatory approval not yet factored in.

- **Governance** – To become a realized mode, and for a network of routes to be developed, regulatory agencies at different levels will need to collaborate to develop a governance and regulatory structure to mitigate risks and support the implementation of Hyperloop.
AECOM undertook this study to inform the discussion on whether Hyperloop could be developed into a viable technology for passenger and freight transportation. The study has not generated any findings that would suggest a fatal flaw in the concept, or the steps taken to actualize the technology. However, there remain a significant number of areas where challenges persist. At this stage, the assessment suggests there is nothing to prevent Hyperloop from becoming a viable mode of transportation, although determining when the technology might be ready for commercial use is not possible at this point.

As a way to measure the potential of the system, Hyperloop is being compared to existing transportation modes. For many possible Hyperloop applications, the primary alternatives are high-speed rail and MagLev. The technical specifications of Hyperloop (if fully realized), would give it a significant advantage in terms of speed over the other modes, but the claim that it could be delivered at a lower cost is now in doubt. This likely means the application of Hyperloop will occur in less price-sensitive corridors, where journey time savings are more important to the demand base than price.

Hyperloop remains an exciting technology capable of changing our perception of travel and transportation in the traditional sense. Given humankind’s achievements over the last decade alone, there is no doubt that certain technological hurdles will be overcome with advancements in digital and electronic technology. However, important issues remain surrounding safety, security, and operations. The challenges may not be insurmountable, as demonstrated by the strides taken during the infancy period of the technology. But to speculate on when Hyperloop will mature to a stage where it can be implemented commercially is not possible at this time. Given the remaining obstacles, it is difficult to see an operating passenger Hyperloop pod until well into the next decade at the earliest.
APPENDICES

A. Reviewed Published Hyperloop Articles and Reports
B. Literature Review
C. Hyperloop Technology Questionnaire
D. Questionnaire Responses
E. Hyperloop Technology Company Overview
F. Python Modelling Process
G. NASA TRL Definitions
H. Economic Questionnaire to Hyperloop Companies
APPENDIX

REVIEWED PUBLISHED HYPERLOOP ARTICLES AND REPORTS
Appendix A

Appendix A – List to Published Hyperloop Articles and Reports Links

These have been listed and organized using the categories: ‘Public Agencies’, ‘Economic Analysis’, ‘Corridor/Logistics Studies’, ‘Engineering Design’ and ‘Other Documents Reviewed’. For ease of reference the same colours have been utilized as per Appendix B

A0: Alpha Paper


A1: Public Agencies


A2: Economic Analysis


**A3: Corridor/Logistics Studies**


**A4: Engineering Design**


A5: **Other Documents Reviewed**


This report seeks to establish the feasibility of the Hyperloop concept for both passenger and freight modes, by looking at a number of the engineering challenges, safety concerns, and more broadly the feasibility of the system.

Details: The passenger service section provides an overview of topics such as trip time, frequency, comfort, and capacity. In addition, different market examples, such as Los Angeles - Las Vegas, Dallas - Houston, and Dubai – Abu Dhabi, were considered.

The report acknowledges that Hyperloop can provide significant speed advantages over traditional modes but that passenger comfort and connections into existing transportation networks (potentially because Hyperloop terminals might not be located downtown) remain challenges to be addressed. In terms of Hyperloop’s application for freight, the report surmised that Hyperloop would not be in a position to compete with sea or air cargo, due to the long distances required and the existing transit terminals. However, there is an opportunity for Hyperloop as a connector from these transfer terminals to final destinations, as this could alleviate the current throughput bottleneck issue occurring at these transfer sites.

Policies & Framework: The report outlined a number of policy considerations, the differences between government and private investment mechanisms, and further areas that need to be researched, such as safety and legislation. The discussion on safety included the current concepts for emergency exits, required distances to stop, and earthquakes.

Status: The report also looked at cost and considered the differences between the original proposed cost and other estimated costs for Hyperloop, while comparing these to other modes such as air and high-speed rail. The review found the cost of land acquisition varied considerably between the different sources. The final section of the report lists a series of questions generated through the development of the report, which need further study. They include topics such as cost, weight, size, and governance of the system.

The article provides critiques of the sources used throughout, such as when discussing the estimated fare price originally provided, noting that actual operating costs need to be defined further.
This report is based on a combination of literature reviews and interviews with Virgin Hyperloop One and Hardt. It notes a previous study conducted on this topic, and the research in this paper builds upon that previous work. It begins by describing how Hyperloop could be beneficial in the context of the Netherlands in terms of potential economic opportunities, before outlining its objective to examine whether a test track should be implemented within the country.

Details: The report introduces seven scenarios for a test site, four Innovation Strategies, and four focus areas. The first area of focus for research is spatial integration, noting that 20 potential locations were assessed and further refined to 8 (based on technical aspects), 3 (based on various criteria), 2 (based on proximity to passenger service), and 1 (based on factors such as the environment). The chosen location for a test site was determined to be Vogelweg, with the reasons outlined including having sufficient space for a test site, and future connection opportunities in that location.

Engineering Design: The second focus area reviews the technology and the different components of the system, such as the use of magnetic levitation, the creation of a vacuum environment, and passenger safety. The third focus of the report was economics with the costs of a potential system as the main topic, discussing data for various components such as pods as well as potential benefits of the technology for connecting major hubs such as airports.

Policies & Framework: The final section looked at the role of government in Hyperloop, with the report noting that the development of safety regulations would be a government responsibility.

Status: The various test facility scenarios were summarized. It is acknowledged that ‘Scenario 3a’, a scaled-down version of the Hyperloop concept that would allow for low-speed testing by multiple pod designs, would provide the greatest benefits while keeping development costs low. The report closes with concluding results and recommendations, namely that a short test track should be constructed, and an Innovation Program for Hyperloop should begin, supported by the government. This report provides evidence of other public entities showing interest in supporting the development of Hyperloop, and the recommendations include proceeding with the development of a test facility with backing from the public sector.

This report examines how the Hyperloop concept, when applied in the United Kingdom, could impact the supply chain and provide a stimulus to the British economy.
**Details:** The report opens with an overview of Hyperloop, outlining the different organizations involved, the various concepts and testing facilities, then explores the challenges of Hyperloop, examining topics such as capability requirements, governance, and design of the system. From there, the report shifts focus to the context of the UK, beginning with the different resources within the country, for example, different companies that could facilitate the supply of components required for propulsion. The financial presence in London is also noted as a potential driver for new transportation technology. Potential routes are presented with considerations for each, such as Liverpool to Leeds through Manchester and from Wales to Scotland. The report also identifies “Hyperloop Lite”, which is a concept for freight transportation, proposed to be smaller and slower than the current Hyperloop design.

**Policies & Framework:** The report acknowledges a significant talent pool already exists within the UK to drive forward both technology design as well as the regulatory and legislative requirements, with the rail experience within the country cited as beneficial for regulation development.

**Engineering Design:** The report seeks to set out a framework for the development of Hyperloop, leveraging existing organizations and industries that can support the design and construction of the system. The report notes that a significant number of design challenges remain, an example being the weight of batteries to go onboard the pods potentially being as much as 40 tonnes in order to store sufficient capacity.

**Status:** Findings suggest that the UK would have many of the components and required interest and investment to make Hyperloop a feasible enterprise. It recognizes that the Hyperloop industry could provide many different benefits, both economically and through improved connectivity to the country. The report also recommends six Government initiatives, covering topics such as hosting sector events, combining organizations for a streamlined development, and reviewing the opportunities and feasibility for the local design of different Hyperloop components. The report enjoyed collaboration from multiple organizations involved in the Hyperloop industry, with interviews and shared data being gathered to support the validity of the various findings and concepts presented.

**Details:** This is an overview report on the current status of the Hyperloop industry, with a focus on providing recommendations for the Dutch government. Multiple aspects of Hyperloop are examined throughout the paper, consisting of topics such as levitation, propulsion, the pod, the tube, and vacuums. The information is presented and assessed from a general perspective, outlining the benefits and constraints the components may contribute to a system. In addition, more detailed analyses were provided regarding anticipated capital costs, the design and development of a hypothetical network scenario, and system safety analysis.
Policy & Framework: As well as reviewing and summarising various elements of Hyperloop technology, the report also looked to provide analysis and information on several areas of direct interest to public bodies potentially responsible for legislation/regulations and national/international development. As part of the analysis conducted, a hypothetical Hyperloop network spanning Europe was developed and assessed based on existing short-haul airline data. In the scenario, it is assumed both Hyperloop and air travel are simultaneously available and that, by offering journey time savings and releasing latent demand, Hyperloop could replace two-thirds of all short-haul airline trips by 2040.

Another factor the report brings forward is the concept of a ‘Safe Haven’ within the Hyperloop network, which acts as a location for safely stopping in an emergency. This system is similar to the hard shoulder, sidings, and emergency divert airstrips that are planned and provided for other transportation modes. Given the importance of this safety measure, it is possible this could become a compulsory design feature of any Hyperloop route.

Given the scale of the European continent and the large number of major urban areas, it is likely that many routes will be developed across international boundaries and will look to connect with other proposed routes. In order to ensure systems can operate in different countries and connect with each other, the report recommends that standardized Hyperloop regulation documentation/guidance is produced within the industry.

Overall, the report separates results into two main categories: the first is the need for standardization through infrastructure, coordination of entities, and implementation of a long-range testing unit. The second category identifies the need for a regulatory organization, the potential for public-private partnership involvement, and considerations for the placement of strategic connections which could help to build a larger network.

Status: This report provides useful insight for government bodies looking to understand some of the key elements of Hyperloop as well as exploring what some feel the next steps for the public sector might be in preparing for/pushing forward this technology. The discussion on uniform design and regulations in Europe is quite important; however, the existence of the European Commission provides a perfect forum for this. Since North America does not have an equivalent entity at present, this may be a topic for future consideration in determining how Hyperloop could work across the US, Canadian and Mexican borders. The concept of providing a safe area separate from the ‘mainline’ is important to acknowledge, equally the report establishes that spacing of these should be sufficient to allow pods to fully evacuate before another pod arrives.
Economic Analysis

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<tr>
<th>04</th>
<th>Title: Article: Shared Value Potential of Transporting Cargo via Hyperloop (2016), Werner, M., Eissing, K., Langton, S.</th>
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<tbody>
<tr>
<td></td>
<td>Publisher: Frontiers In Built Environment</td>
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<td>Link: Shared Value Potential of Transporting Cargo via Hyperloop. Article.</td>
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**Details:** The article opens with an overview of previously completed studies and a general description of Hyperloop, and states its objective to use a hypothetical 300km Hyperloop system in Northern Germany for cargo to determine shared value. The four performance indicators of speed, frequency, payload, and energy consumption, derived from the Hyperloop Alpha paper (Musk, 2013), are used. The paper identifies as limitations of this study the dearth of previous studies available to reference and the numerous assumptions needed, for example, the assumption that there will be two tubes.

**Engineering Design:** The analysis section is based primarily on information regarding freight trucks in Germany, stating the possibility of approximately 214,000-380,000 fewer trucks if the hypothetical Hyperloop in this article was implemented. It is organized into eight sections, consisting of travel speed, operating costs, safety, noise pollution, air pollution, climate effect/carbon footprint, separation effect, and property efficiency, and running maintenance costs. The article closes with an assessment of the different components of these factors in monetary terms.

**Status:** The results of the article purportedly show an estimated €660-€900 Million worth of shared value among the eight factors is possible with the implementation of the hypothetical Hyperloop. Overall, it is claimed that all of the factors would benefit. It is important to note, however, that not all of the subcategories analyzed were readily translatable to a monetary value. For example, transportation price for cargo (under operating costs), reliability (under safety), and separation effect were acknowledged as being unable to be costed. This determination was supported by a brief explanation, typically stating a need for more information. The report finds the opportunity that Hyperloop could create for the freight sector in Germany to be significantly faster and cheaper in terms of freight transportation while offering significant environmental cost savings as well.

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<th>05</th>
<th>Title: Article: Hyperloop: No Pressure (2016), Ross, P.E</th>
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<tr>
<td></td>
<td>Publisher: Institute of Electrical and Electronics Engineers (IEEE SPECTRUM)</td>
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<td></td>
<td>Link: Article: Hyperloop: No Pressure</td>
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**Details:** The article opens by explaining the original concept created by Elon Musk before noting a design contest that was held for Hyperloop. It takes a historical approach, looking at examples, such as Robert H. Goddard and Robert Salter, who previously created similar concepts using rockets and vacuum capsules, respectively. Costing is also discussed, with a series of different opinions presented. It is noted that this will become an increasingly important topic as the technology development progresses.
**Engineering Design:** The article notes that a key component of the original Hyperloop concept is the identification of ways to improve it. Citing, as an example, the inability of current market available compressors to perform above certain speed limits, meaning the design will require updating for functionality at higher speeds. Technical considerations, such as the vacuum component, as well as potential issues (e.g. emergency evacuation of the system) were also discussed, highlighting some of the many areas that are yet to be researched.

**Policies & Framework:** The article recognizes that the influence of the political arena is likely to add complexity to implementation and regulation of the technology and that this could hinder development and also dictate where Hyperloop can be deployed.

**Status:** No findings from “Hyperloop: No Pressure” are explicitly stated nor is there a summary section of the information. The article, however, raises a number of points, such as the consideration that many components of the Hyperloop system require further understanding and development, and there remain many different perspectives on costing and use of the new technology. In addition, the author raises questions over some of the claims and statements of the original Alpha paper and queries how realistic some of the perceived benefits actually are.

While not academic in nature, this article provides an outline of considerations regarding the Hyperloop concept. It makes use of various industry experts with knowledge of topics related to Hyperloop, such as Carl Brockmeyer, whose experience lies in the vacuum business for Hyperloop Transportation Technologies, and CEO and founder, Dirk Ahlborn. It adds to the understanding of the Hyperloop concept while simultaneously questioning the initial benefits claimed by the Alpha paper and identifying areas where further research and understanding are needed.

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<th>10</th>
<th>Title:</th>
<th>Article: Initial Order of Magnitude Analysis for Transport Hyperloop System Infrastructure (2017), TransPod</th>
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<td></td>
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**Details:** The article focuses on the estimated capital costs and provides an overview of the company organization. A cost overview was outlined, through a series of tables, proposing an estimated total of $28,895,000 CAD to construct per km. The assumptions inherent in this cost estimate are provided, including assumed component dimensions, foundation conditions, and costs not included, such as insurance and taxes. Of the different phases identified, the phase relating to the tube construction is the highest cost at $11,063,000 CAD per km or 38.3% of the total per km cost.

**Engineering Design:** A general description of system components is given with a focus on a potential elevated structure, noting that these are safer and cheaper compared to on-the-ground and underground guideways, respectively. In addition, the tube designs and emergency exits were outlined, along with some example dimensions for the identified components.
Status: The article acknowledges more can be done to decrease the cost and that the costs for on-the-ground and underground guideways should also be calculated.

It compares these findings with high-speed rail, noting that high-speed rail could cost 50% more to construct. Based on the figures given in the background section of the report, the proposed high-speed rail running from Toronto-Windsor could cost $55 Million (based on 250km/h) to $149 Million (300km/h) per kilometre compared to the estimated $28,895,000 CAD per km for the TransPod design. Figures provided for the high-speed rail only specify that they came from a government study, but neither the exact name of the study nor a link is supplied. Additionally, how TransPod collected their costing information is unclear. The introduction notes that data for engineering and costing was used from other projects but did not give any further information.

This article was produced by TransPod from information regarding their designs and projected costs. In addition to not specifying where their data came from, the reference to other sources is limited to a study on the proposed high-speed rail in Ontario, the important proponents Robert Goddard and Elon Musk, and noting NFPA130 (National Fire Protection Agency) for regulations. The article concludes that, given the significant cost savings predicted compared to high-speed rail, the Hyperloop concept should be considered along the Toronto to Windsor corridor.

| 11 | Title: Article: The Hyperloop Concept compared to the economic performance of other means of transportation (2017), Paczek, P. |
| Publisher: Kozminski University, Poland |
| Link: Article: The Hyperloop compared to the economic performance of other means of transportation |

Details: Following a brief overview of the Hyperloop concept, with a focus on the Hyperloop Alpha paper (Musk, 2013) and the different organizations within the industry, this article is largely an economic comparison of Hyperloop to three other modes of transportation—road, rail, and air—in the context of 12 different routes throughout Poland both for current and potential infrastructure, such as high-speed rail locations.

Economic Analysis: The methodology explains that the performance measures of “Cost of Velocity for Passenger” and “Total Yearly Cost per Kilometer per Passenger” were used through a cost-effectiveness analysis. Data were assessed for components such as distance, passengers per year, and travel time, speed, and cost. For instance, the mode with the shortest journey time was determined, presently, to be air. The cost to ride on the Hyperloop was estimated to be cheaper than travelling by road in an automobile based on a formula that considered infrastructure cost, the value of time and total ridership. In terms of cost in relation to velocity, the article states that road travel by car might be 6-7 times more expensive than riding on Hyperloop. Lastly, the total yearly costs per kilometre per passenger were determined to be similar for the modes of Hyperloop, road, and conventional rail.
**Status:** The findings indicate travelling by road could be 6-7 times more expensive than riding Hyperloop and that high-speed rail could also be more expensive than Hyperloop (approximately by 50%), but other modes may be similar in terms of total yearly cost per kilometre per passenger. Despite the use of multiple sources, limitations are acknowledged in terms of how we can take this forward. For instance, it is acknowledged that commuters were not considered in the cost analysis section and that some of the data were aggregated for the calculations. The study finds Hyperloop to have a lower potential cost per km than high-speed rail and that it will compare favourably to other modes. However, the article also identifies that the main costs for Hyperloop are in the construction phase, and if these were to be reduced its overall cost to users would decrease. It notes that additional considerations such as weather exposure and energy and land use should be taken into account.

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<th>16</th>
<th>Title: Article: Railways of the Future: Evolution and prospects of High-Speed Rail, MagLev and Hyperloop (2017), Gonzalez-Gonzalez, E. &amp; Nogues, S.</th>
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<td></td>
<td>Publisher: Civil Engineering – Urban and Spatial Planning</td>
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<td></td>
<td>Link: Article: Railways of the Future: evolution and prospects of HSR, MagLev, and Hyperloop</td>
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This article is a perspective piece providing an overview of High-speed rail, MagLev, and Hyperloop.

**Details:** The article opens with the examination of high-speed rail, explaining how Japan led the industry, opening its system in 1964, followed by France in 1981 (despite a gas concept from 1969), Germany in 1991 (including considering the freight implications), and Spain in 1992. An overview of MagLev technology is provided, noting key dates: 1934 when the idea was introduced, the creation of the German system in the 1970s, and the High-Speed Surface Transport that Japan introduced in 1972. Other planned examples are the USA’s Inductrack and Japan’s SCMagLev. Lastly, the Hyperloop section begins by presenting the concept as advanced by Elon Musk and acknowledging the historical work done in this field, ranging from 1847’s Atmospheric Railway by Brunel to 1960’s Aerotrain by Bertin.

The second part of the article acknowledges potential challenges within the three different modes and notes that, while high-speed rail is used in various locations and is expanding, there are critics due to its relatively high cost per km. MagLev has many operational and rider benefits, but it is also a high-cost option. In comparison, Hyperloop offers quicker trips, but discrepancies remain surrounding the estimated costs, which range from €6.6 Million/km when first proposed to as high as €52-71 Million/km in other cases.

**Engineering Design:** It is noted that high-speed rail and MagLev are now grouped under High-Speed Ground Transportation (HSGT). Differences in the approach to high-speed rail between countries included modular systems vs fixed systems and the implications of using a track size different than the rest of the country. For instance, although both France and Japan used a standard track gauge for high-speed rail, only the French model could be used on other local tracks as the Japanese tracks were different gauge sizes. Two categories were noted within high-speed rail, infrastructure for train travel at or over 250km/h and that which is suitable only up to 200km/h, as per the European Union.
**Status:** This article claims that, in the medium-long term, current systems will be replaced by new emerging technologies such as Hyperloop. However, the definition of “medium-long” is not provided. Neither does the article discuss when these systems may be actually implemented, aside from the SC-MagLev in Japan scheduled to open in 2027.

The report establishes and reviews two main competitor modes to Hyperloop and examines how Hyperloop compares to these two more established modes. Due to the fact that Hyperloop has not been implemented in any corridors to date, much of the information is still an approximation or based on hypothetical research. This limits the reliability of the findings and recommendations as the level of detail and understanding for the two other modes are much further advanced.

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<tr>
<th>Title: Study: Multicriteria Evaluation of the High-Speed Rail, TransRapid, Maglev and Hyperloop System (2018), M. Janic 2018, Netherlands</th>
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<tr>
<td>Publisher: Delft University of Technology</td>
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<tr>
<td>Link: Study: Multicriteria Evaluation of the High-Speed Rail, TransRapid, Maglev and Hyperloop System</td>
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This report/paper is part of a multicriteria evaluation of the high-speed rail system, TransRapid MagLev (TRM) and Hyperloop transportation mode comparison. A SAW (Simple Additive Weighting) Method was used to assess the performance of these systems. Performance indicators included operational, economic, environmental, and social measures, which are defined and modelled respecting the interest and preferences of particular stakeholders, including users/passengers, transport operators, local, regional, national authorities and investors or community members.

**Details:** The multicriteria evaluation of three high-speed transportation systems - high-speed rail, TransRapid MagLev, and Hyperloop - includes a multidimensional examination of the performance of each mode based on the development of a series of analytical models. This particular assessment was based on an existing corridor connecting Moscow and St. Petersburg in Russia, where a high-speed rail service, with speeds up to 250km/h, currently operates. For the purpose of the study, it was assumed that each of the three high-speed systems would operate exclusively in the right of way.

**Policy and Framework:** The three modes are all at various stages of development and deployment, with high-speed rail being the most commonly found and Hyperloop yet to have been physically deployed in any location. In conducting the multicriteria analysis, the weighting is applied to the various categories based on the perceived importance of these factors to the wider community, for example, noise and required rolling stock are weighted higher with the contribution to GDP being weighted low. The results suggest that Hyperloop would offer the best solution, predominately as a result of its low energy usages and operating cost. The paper goes on to discuss whether the multicriteria approach and weighting of the categories is the best approach but surmises that, of the other methods available, this is best suited for the purpose.
**Status:** The paper uses a different approach to the more commonly cited cost-benefit analysis in assessing the three modes, and still claims that Hyperloop scores the best. This suggests that even when some of the more compelling financial arguments for Hyperloop are given less weight, aspects such as noise and Greenhouse Gas benefits still help Hyperloop outperform other high-speed modes. There remain a significant number of assumptions as part of this comparison, including that only one mode would operate within the corridor and would therefore, lacking competition from other modes, enjoy 100% of the market share. This would negate factors such as ticket price and user preference. The evaluation also implies high uncertainty in expected performances. Impacts of external and internal disruptive events are not considered. Therefore, future evaluation of this consideration is required, as well as a comparison that includes air travel.

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<th>22</th>
<th><strong>Title:</strong> Academic Paper: Hyperloop in Sweden: Evaluation Hyperloops viability in the Swedish context (2018), Magnusson, F., Widergren, F.</th>
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<td></td>
<td><strong>Publisher:</strong> KTH Royal Institute of Technology, Stockholm</td>
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<td></td>
<td><strong>Link:</strong> <a href="#">Academic Paper: Hyperloop in Sweden: Evaluation Hyperloops viability in the Swedish context</a></td>
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This student thesis aims to give an overarching understanding of the Swedish transportation market and whether there is an opportunity for the Hyperloop concept to add to the national network.

**Details:** As Hyperloop technology has yet to be deployed anywhere, due to being in the early stages of development, it presents an interesting high-speed transportation mode case study. In order to understand whether the concept can be applied in Sweden, three frameworks, characteristics of diffusion, the multi-level perspective and technology readiness level, were used to assess Hyperloop viability.

**Policy and Framework:** The study explores, through a mixture of academic research on Hyperloop and interviews and analysis of the existing Swedish transportation network, how Hyperloop might impact the current system. The research included assessing how disruptive technologies fare in established markets and what factors impact early adopters. The research found that in the Swedish context, significant focus was placed on the environmental impacts of transportation modes (with a current 3% growth per annum in transportation-related CO\textsubscript{2} emissions a concern). This bodes well for Hyperloop as it is considered to be a fairly low producer of emissions and requires significantly less energy than other high-speed modes.

The study also finds that transitions to new modes can be difficult and, without sufficient momentum to trigger such a move, can often stall. A review of the current transportation network identified a lack of existing supply, particularly for high-speed service, and this could provide the opportunity for Hyperloop to be implemented and adopted by sufficient users to make it viable. The study goes on to find sufficient need and opportunity for the implementation of Hyperloop to be successful, on the condition that it is capable of offering the speeds and benefits currently claimed by developers.

**Status:** The report provides an interesting perspective on how Hyperloop can benefit a particular country. It assesses the national network and identifies an opportunity to alleviate insufficient rail capacity and unreliable service with a new high-speed service.
Such a study could help justify why other countries should take a more holistic view of the transportation network at a national level, in order to identify opportunities to shift the national perspective on transportation. The report also makes a recommendation regarding public-sector involvement in not only testing and regulating the technology but in the opportunity that exists to use it as a catalyst to provide new connections and potentially stimulate growth in targeted areas.

In India, so far, there have been two proposals for Hyperloop links, one connecting Mumbai with Pune and the other between Amaravati and Vijayawada.

**Details:** This article presents a summary of the industry to date and provides a timeline of the various significant steps that major players in the development of the technology have taken so far. It describes the general concept of Hyperloop from Elon Musk’s Alpha paper. It also describes the distances, speeds, and cost of the proposed system, noting the challenges of working with air resistance and ground friction, and acknowledges that a standard Hyperloop design has been generally established within the industry.

**Engineering Design:** The article outlines the contributions of various organizations and entities to the development of Hyperloop technology. For instance, when Virgin Hyperloop One proposed passive MagLev over a compressor, Anasys Corporation identified that the Hyperloop capsule should take a different form from the original concept, and the use of a wider tube was identified by Open MDAO. It also discusses the needs and design of testing facilities, including the proposed locations. It identifies that many different organizations are working within the Hyperloop industry on various components of the design and in different locations. Some of the material identified in the article dates to 2012, which shows that the industry has progressed quickly within a short time frame. This also shows that concepts and understanding have significantly shifted since then.

**Status:** The article highlights two areas that need to be addressed. Firstly, that all of the organizations in the industry should “accept” the design of steel tubes and MagLev capsules; however, no sources are provided to justify this statement. Secondly, the estimated timeline for Hyperloop to be operational, (running within 10 years, “cost-effective” within 20), is difficult to substantiate because, despite quoting a future date for a Toronto to Montreal Hyperloop study and a couple of total estimated costs from other studies (such as the original $6 Billion cost assumed to be from the Hyperloop Alpha paper but not specified), the focus of the paper is not on determining timescales for implementation and so the claim regarding the timescales for implementation are surprising.
This paper sets out to critically examine Hyperloop, opening with a brief outline of Elon Musk’s concept and the potential benefits to transit it could deliver including faster travel times; lower energy consumption; commercial integration of cities and labour markets; and reduced congestion. It alludes to a number of other companies and countries who are conducting feasibility studies with the aim to commercialize Hyperloop by 2021 and notes that there are potential issues related to economics, safety, and passenger comfort that require real-world demonstrations to overcome.

Details: Due to UK topography, the paper claims Hyperloop is more likely to achieve success overseas in countries offering political /economic support and flat landscapes. In December 2017, the Science Advisory Council for the Department for Transport produced a position paper stating Hyperloop to be a couple of decades away within the UK but expressing commitment to monitoring development, supporting the design, development, and delivery of Hyperloop and continuing to explore its potential application as a transport mode.

The paper sets out to determine the validity of commercial claims in relation to travel time, capacity, land implications, energy demand, costs, safety, and passenger comfort. It highlights key gaps in knowledge requiring further research. Through analysis of the key strengths and weaknesses, the research outlines potential applications of Hyperloop and reflects on their wider implications for society.

Based on the SpaceX model from Los Angeles to San Francisco (35 minutes Hyperloop, 2 hours 35 mins high-speed rail, 1 hour 20 mins air travel), timing to travel between London and Edinburgh was determined: via Virgin Hyperloop One, the trip would take 50 minutes; via high-speed rail, the trip would take 3 hours and 37 minutes; and via air travel the trip would take 1 hour and 10 minutes. In terms of the boarding process, Hyperloop is anticipated to be smooth and efficient, unless passenger numbers exceed pod capacities resulting in queues and boarding time increases. Overall, Hyperloop achieves the shortest station to station travel time, but other factors (e.g. possible boarding and acceleration/deceleration restrictions) significantly increase the overall journey time making it less attractive.

Engineering Design: Based on Elon Musk’s proposal, Hyperloop capacity would be 840 passengers per hour with pods holding 28 people departing every 2 minutes. Hyperloop Transport Technologies suggested a capacity of 3600 an hour based on pods holding 40 people departing every 40 seconds. However, the viability of pods departing every 30-40 seconds is questionable as pods travelling 760 miles per hour will have a maximum deceleration of 0.5 gs, which is equivalent to 10.9 mph per second. At that rate of braking, it will take pods 68.4 seconds to come to a full stop. Therefore, minimum pod separation is closer to 80 seconds, which would allow 45 departures per hour and capacities of 1260 (28 people per pod) or 1800 (40 people per pod). In comparison, the current capacity of air travel is 400 passengers per hour and high-speed rail capacity is 12,000 per hour within California, USA.
**Status:** This paper validates commercial claims in relation to travel time, capacity, land implications, energy demand, costs, safety, and passenger comfort while highlighting key gaps requiring further research.

In order to fully estimate the impacts, real-world trials are required to prove the validity of the concept (the cost of construction may undermine the economic benefit), determination of realistic capacity, and carrying speeds. Overall, it is suggested that Hyperloop is at least 20 years away within the UK but could be a viable mode of transport within the Middle East.

Hyperloop may provide solutions to current airport capacity as an inter and intra airport connecting service and by eliminating the need for construction of additional runways. Despite key benefits in relation to speed and energy, other factors raise doubts over the viability of Hyperloop as an alternative transport mode. In addition to economic and engineering issues, there are significant barriers to overcome regarding human factors such as physical and mental passenger comfort, noise, vibration, motion sickness, accelerating and decelerating forces, and the mental strain of travelling in an enclosed environment. Overall, it is unrealistic that Hyperloop will be in the UK by 2021, as currently claimed by multiple sources containing significant variations in estimates. However, it's feasible that with further research, testing, and refinement, the Hyperloop concept could progress in some locations and will likely change the face of the transportation industry.

Hyperloop is examined as an efficient alternative of high-speed rail and air passenger transport for long-distance passenger transport. This paper explores the performances of Hyperloop and compares them to high-speed rail and air travel. The following performance measures are analytically modelled and compared to high-speed rail and air travel: (i) operational performance; (ii) financial performance; (iii) social/environmental performance.

**Details:** Improvements to aviation including capabilities, strategy, government regulations, size, speed, and safety have seen air travel in Europe increase by 45% between 2001 and 2013 while other methods (car and train) have remained stable and declining (buses). Similarly, the high-speed rail system in Japan relied on an entirely new network with new technical standards. In Europe, high-speed rail systems have been developed for existing corridors, where infrastructure has been upgraded or replaced in certain locations with specifically customized solutions to allow maximum speeds equal to or greater than 250 km/hour.

In order to compare these systems with the Hyperloop system, multiple statistical equations were used to calculate the technical productivity; fleet size; and ultimate capacity of stations, line segments, line/tube, and transport to provide a method for direct comparison.
Quality of services was also considered, as this influences the attractiveness of the Hyperloop system, including door-to-door travel time, transport service frequency, and reliability of services. The door-to-door travel includes egress time, schedule delay, in-vehicle time, and interchange time between different Hyperloop vehicles. Access and egress time depend on the interconnectivity between the Hyperloop system and the speed of pre- and post-haulage systems and the density of stations. Waiting time depends on the frequency of Hyperloop services.

The need for interchanges generally diminishes the overall quality and makes trips less convenient. Hyperloop operates autonomously, and within an enclosed environment. This makes the service reliable in terms of human-related delays and weather delays. Furthermore, the financial performance of the Hyperloop system is defined by revenues - costs and profits, and the difference between them. The zero-profitability achieved by competitive prices could guarantee the bottom line for the stable economic viability of the Hyperloop system. Cost considerations included the cost of vehicles, the capital cost of track construction, the capital cost of station/terminal construction, annual cost, maintenance cost of infrastructure and rolling stock, operating cost, and overhead costs. Revenues and processes, noise, safety, and energy consumption and emissions were also considered.

**Status:** Overall, the greatest difference between the Hyperloop mode and the two other modes lie in vehicle capacity, vehicle cost per seat per km, and the Greenhouse Gas emissions. In all cases, the values were low for Hyperloop. Low vehicle capacity could be offset by coupling vehicles, but this could cause technical challenges (moving through curves, etc.). Low vehicle cost per seat per km is explained by the extremely high speed as well as the absence of energy costs. The cost of solar cells is incorporated into the line infrastructure costs. Further research is required in terms of energy consumption and Greenhouse Gas emissions at all points of development and operation. The estimation of social performance could also be improved based on access and the creation of new jobs.

The main operational result claims the capacity of the Hyperloop is low, which implies a low utilization of the infrastructure. Because the infrastructure costs dominate the total costs, the costs per passenger-km are high compared to those for high-speed rail and air travel.

Hyperloop performs very well regarding the social/environmental aspects because of low energy use, no Greenhouse Gas emissions during Hyperloop operation and hardly any noise. Safety performance needs further consideration. The review concluded that Hyperloop systems offer promise for relieving the environmental pressure of long-distance travel, but has disadvantages that include concerns over operational and financial performance.
Details: This study was conducted as part of an academic thesis, using axiomatic design to investigate the implementation of both high-speed rail and Hyperloop along the eastern coast of Australia, connecting Sydney, Canberra, and Melbourne. Axiomatic design is used at a preliminary level to quantify the relative uncertainties. A cost analysis was conducted to determine the difference in the cost of each system and to model the future and net present value of each project over a fifty-year timeline. The paper was based on the Australian government's desire to provide a high-speed connection along the country’s east coast. A feasibility study conducted on behalf of the government by AECOM in 2013 estimated that a high-speed rail project would cost $114 Billion AUD to connect Sydney, Melbourne, Canberra, and Brisbane, and would take up to 50 years to construct.

The paper seeks to explore whether the application of Hyperloop as an alternative to high-speed rail could reduce construction costs and timescales for deployment. The route between Melbourne and Sydney is expected to be fairly straight, and so they could also benefit from the forecast top speeds of Hyperloop (1200 km/hr) compared to the 350 km/hr speeds that had been proposed for high-speed rail.

Mode Comparison: In considering their performance, the paper explores a number of the design elements of both high-speed rail (based on the Chinese CRH3C system) and Hyperloop, examining the underlying concepts that address factors such as energy transfer, airflow, and levitation. Its analysis of Hyperloop considers magnetic levitation and air cushions for levitation, noting that both have advantages. However, there are still significant challenges to overcome for either to be deemed viable.

The findings suggest that a high-speed rail service from Sydney to Melbourne, with a 5-minute stopover in Canberra, operating at 350km/h, could potentially offer travel times between 181 and 215 minutes. By comparison, Hyperloop, using MagLev technology, is theoretically capable of a maximum operational speed of 1,200 km/hour, taking the same journey time to between 56 and 82 minutes. The financial assessment determined the total capital cost associated with high-speed rail to be between $42 and $60.7 Billion AUD while Hyperloop is estimated to cost somewhere in the range of $52.2 to $111.8 Billion AUD, however, this includes the cost of further development to the Hyperloop system, which is $20 Billion AUD alone. If this were removed the lower end of the cost range for Hyperloop could fall below the high-speed rail price. The high-speed rail system is not expected to generate a net annual profit in the investigated fifty-year timeline due to high maintenance and operational costs. The Hyperloop system is predicted to generate a net annual profit, but this is based on assumption, and it is unclear whether the system would be profitable within the comparative fifty-year time period.
Further, according to axiomatic design, the high-speed rail system is projected to cost 20% less than the equivalent Hyperloop system and is 45% less in non-conservative modes. It was determined that the Hyperloop has lower maintenance costs, but the financial model is insufficient to make conclusions on long-term profits.

Status: Overall, using an axiomatic design is not recommended for undeveloped technologies. Therefore, future recommendations of this study include a more thorough investigation of the Hyperloop design, including flow behaviour, levitation mechanisms, and propulsion systems. Doubts remain over the accuracy of the findings in the paper. In particular, the various costing elements have a significant degree of variability built in that reduces certainty, as evinced by the wide price range provided for Hyperloop. Equally, it is acknowledged that Hyperloop expects to have substantially lower operating costs than high-speed rail. However, given the technology’s current lack of development in the market place, it is difficult to assess these costs accurately.

Overall, the paper recommends that policymakers in Australia continue to investigate the feasibility of Hyperloop before committing to a high-speed rail project, as the potential costs and benefits of a Hyperloop system could supersede those of high-speed rail. But without further development and testing to prove the construction and operation assumptions, a full comparative assessment of the two modes remains difficult.

Details: AECOM Canada Ltd, was retained to prepare a submission for a hypothetical Hyperloop network to connect the Toronto-Ottawa-Montreal corridor. The corridor is the most heavily traveled inter-regional corridor in Canada; the metropolitan areas combined contain over 25% of Canada’s population. Average daily traffic on Highway 401 exceeds 450,000 vehicles within the City of Toronto, and it never drops below 20,000 between urban centres along the route. The importance of this connection is also recognized by non-auto passenger carriers. VIA Rail earns 67% of its revenue within the Quebec-Windsor corridor and all major air carriers in the regional market (Air Canada, WestJet, Porter) offer dozens of daily flights between the three cities.

The study considered station locations and corridors for the three cities. Within Toronto, the sites considered included Union Station, Toronto Pearson International Airport, and Highway 401 in the vicinity of Fairview Mall, based on issues such as parking capacity, accessibility, ease of connection and other factors. The Highway 401 corridor can support the Hyperloop but has constraints at existing interchanges and grade separations. Overall, running parallel to the highway is the preferred alternative, reducing incremental impacts such as noise and land fragmentation. Within Ottawa, the ideal location was stated as either Downtown or out by Ottawa International airport, as these would be the most accessible.
Within Montreal, two preferred locations based on accessibility and ease of parking were considered, including the Pierre Elliot Trudeau Airport and Central Station. Due to the many waterways within this corridor - the Trent River (approximately 100 to 150 m wide), Rideau River (100 to 150 m), Ottawa River (500 and 1500 m), Riviere Des Mile Iles (300 to 800 m), Riviere Des Prairies (500 m) – consideration was given to watercourse crossings. Large hydro corridors also cause implications as relocating these are not desirable. Below grade segments may be a preferred solution. Furthermore, geological conditions, green energy and distances and travel time contribute to considerations when determining feasibility. Based on a suggested maximum speed of 1000 km/hour, with additional time for acceleration and deceleration and station dwell time, it would take 25 minutes from Toronto to Ottawa, 20 minutes from Ottawa to Montreal, 45 minutes on the Toronto to Montreal express and 55 minutes from Toronto to Montreal with a stop in Ottawa.

**Mode Comparison:** A number of previous studies have looked at connecting Toronto, Ottawa, and Montreal using a 300 km/hour high-speed rail system. These indicated that the system would be financially viable and generate substantial economic and social benefits to the corridor. As part of this assessment, an airfare scenario was also investigated, with Hyperloop prices set at a level comparable to air travel. In the max-rider scenario, differing levels of prices would be charged to different users in order to increase ridership to the level that the system capacity allows at any time of day. In this scenario, it was expected that Hyperloop would attract passengers from other modes, with about 15 to 20% of auto users, 20 to 25% of air travellers and 30 to 35% of rail travellers shifting to the new system. In addition, 8 million new business trips generated by the Hyperloop connection would also be realized from latent demand. In the max-rider scenario, aggressive price discrimination strategies were applied to maximize profit from the passenger by charging the right amount from each customer type. Thus, the shift in trip modes would be much more dramatic, as other methods such as rail and air travel would struggle to compete. With shorter travel times and lower costs, it is expected that up to 90% of rail trips, 70% of air travel, 60% of bus trips and 40% of auto trips would shift to Hyperloop. Canadian provincial and federal governments are committed to improving transit infrastructure and reducing Greenhouse Gas emissions through electrification of surface transport. A Hyperloop service could reduce travel times along the corridor for 10.8 million users per year, and with the current growth rates in the area, this number is likely to increase.

**Status:** The estimated mode shares are founded on standard modelling techniques; however, the report does not conclusively justify the findings. Given that the forecasts suggest almost 80% of ridership would come from new demand, it is difficult to assess whether the max-rider scenario is viable, which casts doubt on the high modal shift claims. The report also makes little provision for how capital and operational costs would factor into the fare structure, casting further doubt on the ability to operate a pricing structure capable of attracting such levels of modal shift. Equally, as the main benefits of the technology are yet to be proven, the journey time savings, which represent the primary advantage of the mode, are also unconfirmed, additionally impacting modal shift forecasts. Time is required for nascent technologies to become trusted by users, with early adopters usually representing a small proportion of users. As such, it is unlikely that the modal shifts will happen during the early stages following implementation.
**Title:** Article: The potential short-term impact of a Hyperloop service between San Francisco and Los Angeles on airport competition in California (2018), Voltes-Dorta, A. Becker, E.

**Publisher:** Transport Policy (online Journal)

**Link:** Article: The potential short-term impact of a Hyperloop service between SF & LA Airports CA

**Details:** An academic assessment was conducted to determine whether the time-space compression brought on by Hyperloop technology would significantly impact residents’ travel behaviour and household mobility as well as expand airline passengers’ choice of airports for long-distance domestic trips. Catchment areas were determined based on flight frequencies, access times, travel costs and how changes to these criteria (brought on by the introduction of Hyperloop) could impact airport competition in California. The analysis compares long-distance markets, including all itineraries originating in California and ending in another US state, to establish a demand matrix. The study aims to demonstrate how Hyperloop and air travel can be used together to complement each other instead of substitute one another. Furthermore, this will be an important consideration in the economic assessment of potential Hyperloop routes connecting major cities.

**Mode Comparison:** Airport leakage is a phenomenon where travellers avoid using local airports in their regions and instead use other (out-of-region) airports to take advantage of lower fares and more convenient airline services.

The study considers twelve of California’s busiest airports according to annual commercial passenger traffic in 2015 (US Federal Aviation Administration). Airports were divided into two (2) regions (Northern California and Southern California), the northern cluster (SFO, OAK, SJC, SMF, FAT) with a connecting hyperloop station in the north HYN (downtown Oakland), and the southern cluster (LAX, BUR, LGB, SNA, ONT, PSP, SAN) with a hyperloop station in the south HYS (Fernando Valley). The analysis used demand modelling to test the sensitivity of airport passenger demand based on access and catchment area. It determined that should a Hyperloop connection be implemented, it could substantially enlarge the catchment area of particular airports close to a Hyperloop station, and this could alter where airlines choose to operate routes.

**Status:** It was determined that LAX, with its dominance in destinations and frequencies, will benefit the most (in terms of passenger traffic) with a predicted increase of between 3.6% and 7.1% in long-distance domestic passenger traffic. This supports the hypothesis that the airport with the largest level of service would benefit the most from Hyperloop. In contrast, airports lacking a similar level of connectivity are predicted to experience a net reduction in traffic, leading to a shift in airport roles within the California system and substantial changes in how these airports operate in terms of passenger traffic. The modelling in this analysis is based on a number of assumptions regarding the construction, operation and pricing of Hyperloop, which would need to be further examined to assess their accuracy. However, the impact of Hyperloop as a complementary, as opposed to competitive mode to air travel, is important to note. At the same time, the deployment of Hyperloop in almost any form is expected to have an impact on air travel given the anticipated benefits and most likely applications.
Details: Black & Veatch were retained to conduct a feasibility study to assess the construction of a Virgin Hyperloop One (VHO) route connecting Kansas City, Columbia, and St. Louis in Missouri, USA. Virgin Hyperloop One’s approach constitutes an all-electric, autonomous transportation system with forecasted top speeds of 670 miles per hour. The pods float along the track using magnetic levitation and accelerate using electric propulsion through a low-pressure tube, creating no direct emissions and minimal noise within surrounding environments. The cost to build ranges from $30 Million USD to $40 Million USD per mile for linear infrastructure, this is 60 – 70% of the cost to build new high-speed rail infrastructure. By assuming the Virgin Hyperloop One system will create new demand as well as generalized portal locations, it was estimated that ridership could range from 16,300 to 51,500 passengers per day. Projected travel time savings are valued at up to $410 Million USD per year based on a combination of ridership and the 2016 Missouri average hourly wage of $22.18 USD. The study also indicated accident cost savings of up to $91 Million USD per year due to reductions in road-related accidents as a result of modal shift following Hyperloop route implementation.

Mode Comparison: The study evaluated three alignments (I-70 corridor, I-70 and Katy Trail Corridor, and State Highway 50) based on the Virgin Hyperloop One system requirements using optimizer software for the route, with considerations for regulatory and public constraints, and minimal environmental impact. The study estimated the current level of demand between the three cities to be between 21,000 and 28,000 daily trips, with forecast daily ridership numbers based on as high as 75% of all existing trips using Hyperloop, and a significant number of latent demand trips.

The study also examines fare pricing and considers the price likely to be competitive with auto travel if operational costs are covered by the fare. This would be significantly less than current airfares.

The analysis determined that the I-70 corridor route (major east-west artery) is the best-suited alignment for Hyperloop of the three considered. It is relatively straight and well established and allows for future connections to Chicago and Denver. Precast concrete was determined as the most viable option for constructing the vacuum structure due to local ground conditions, domestic availability of materials and skilled labour, and compatibility with heavily automated construction processes. In terms of the construction process, staging areas are proposed at vacuum facilities, which are required approximately every 10 km.

The geology of the area allows for the drilled pier foundations to be tied into limestone bedrock, which has sufficient strength. Shale, on the other hand, has greater weathering potential and may require deeper foundations, which should be considered following the determination of the final alignment.
The I-70 route was assessed under the assumption that minimum requirements for vertical and horizontal curves are met, right of way easements are adequate and minimize the need for new or greenfield right of way, ground clearance of the elevated vacuum structures is 50 ft or greater to avoid existing infrastructure, and permanent right of way of 50 ft and construction easement of 100 ft is available. Assessments pertaining to property acquisition, visual impacts, and public outreach are to be conducted in future stages. It was also noted that a number of streams, rivers, structures, rail crossings, and public structures could impact the selected alignment. Future studies are planned to assess the need for various permits and authorizations from federal, state and local jurisdictional agencies and authorities. It is also expected that a comprehensive environmental impact study will be completed before funding or issuance of major permits.

**Status:** The study examined a key corridor in the mid-west of the United States, and identified an opportunity for a new Hyperloop connection that would help alleviate congestion and provide a faster and cheaper service than air and rail. The lack of modelling to determine modal shift/assignment makes it difficult to substantiate the highly ambitious 75% modal assignment to Hyperloop. Equally, the study suggests pricing should be based on operational costs and does not consider construction cost in its fare structure. If Hyperloop is realized at the speeds envisioned it does have the potential to significantly impact air and rail connections, but such a shift from auto mode seems unlikely given current theory on the advantages that personal transportation modes bring for users.

### Study: Hyperloop in Thailand: Preliminary study on the implementation of a TransPod Hyperloop line in Thailand (2019), TransPod

**Publisher:** TransPod

**Details:** TransPod was retained to conduct a corridor study for the implementation of Hyperloop in Thailand. The Hyperloop technology developed by TransPod is considered against the high-speed rail model proposed by a Japanese Study as part of a pre-feasibility study on behalf of Thanathorn Juangroongruangkit. The potential passenger Hyperloop, spanning from Bangkok to Chiang Mai, will include an extension to Phuket in Thailand and is known as the Chiang Mai/ Bangkok/ Phuket corridor.

TransPod differs from other technologies (SpaceX, etc.) because it uses levitation, propulsion and high-speed power transfer and is not constrained by costly propulsion configurations (MagLev or batteries). The technology is fully electric, linear induction motors run on solar panels above the low-pressure environment tube networks, meaning it's considered environmentally friendly and free of Greenhouse Gas emissions common to other transportation modes. The study utilized a cost-benefit analysis process to assess the application of Hyperloop along this corridor.
**Mode Comparison:** A qualitative analysis was conducted comparing the proposed Hyperloop mode with passenger flights, high-speed rail, car, and bus transportation. The assessment found that Hyperloop was the preferred choice for speed, departure frequency, fuel efficiency, energy efficiency, system downtime, weather resistance, incursion performance, motion sickness prevention, and comfort. In order to forecast future ridership for the proposed Hyperloop line, a pre-feasibility study conducted by the Japanese high-speed rail authority was used as an overview for the current trip distribution and to provide an understanding of what commuters were willing to pay across all existing modes of transit.

The analysis suggested significant journey time savings for commuters, reducing travel time to one (1) hour between the cities while traveling at speeds from 1,000 to 1,200 km/h. Construction costs from Bangkok to Chiang Mai were estimated at $18.90 Million USD per km, about 3% cheaper than the high-speed rail system proposed by the Japanese study at $19.43 Million USD per km.

The report also discusses some of the anticipated wider benefits of implementing the Hyperloop corridor including decentralization of the population from Bangkok; reduction in Greenhouse Gas emissions by switching to Hyperloop; safety improvements due to fewer automobile accidents and significant cost savings to the economy of accidents; and the economic stimulus such a system would add to the economy.

**Status:** The report finds the economic and wider benefits of implementing a Hyperloop system in Thailand to be significant. However, the integrity of the data used for establishing ridership and modal share is limited and outdated. Equally, when considering mode share, it is assumed that users will transfer due to the journey time savings. However, there are a number of other factors that need to be included when calculating modal shift such as final destination, the purpose of the trip, accessibility factors, and passenger comfort. Overall, this study has shown that the TransPod Hyperloop technology has the potential to be more competitive than a high-speed rail alternative, and could provide significant economic and environmental benefits.

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<th>Title:</th>
<th>Study: Great Lakes Hyperloop Feasibility Study - Northeast Ohio Areawide Coordinating Agency Draft (2019)</th>
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<tr>
<td>Publisher:</td>
<td>Hyperloop Transportation Technologies and Northeast Ohio Areawide Coordinating Agency</td>
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<td>Link:</td>
<td>Study: Great Lakes Hyperloop Feasibility Study</td>
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**Details:** Hyperloop Transportation Technologies (HTT) and Northeast Ohio Areawide Coordinating Agency (NOACA) have produced a regional feasibility study the application of Hyperloop between Chicago and Pittsburgh, via Cleveland. The premise of the study is based on the underlying assessment of East-West movement in the Northern half of the US being funnelled through the Cleveland to Chicago corridor.

The report considers there to be considerable growth opportunity within the corridor, which is currently underserved by transportation connections. It follows a formal business case process (in line with requirements for USDOT funding guidelines) to establish the basis and benefits of implementing a Hyperloop connection between Pittsburgh and Chicago via Cleveland.
Three alternatives are considered in its assessment including a simple point to point through greenfield sites; multi stations along a route that follows existing transportation corridors; and a hybrid version. The report considers and models a number of factors such as journey time savings, the value of frequency, economic growth and demand on other transportation modes.

It also examines the possibility of a freight service using the GOODS model system. Hyperloop freight is compared to rail, road and air alternatives to gauge what opportunities exist for the implementation of such a service.

**Mode Comparison:** The report considers the impact a Hyperloop system would have on both existing and future mode shares within the study region. The findings reflect a belief that a Hyperloop system would create a mode shift of between 25% and 32% of all trips to this new service, based on analysis that suggests the value of time, frequency of service, and increase in congestion for automobiles will be deciding factors for users. The study also suggests significant induced demand would be realized by introducing the service, with as much as 32% of total ridership coming this way. The report considers the trip purpose of potential Hyperloop users, with 15% being commuters and 36-39% being business users (depending on the scenario).

The freight scenario explores how Hyperloop might benefit the existing freight network. Modelling analysis results suggest Hyperloop can provide opportunities in the freight market by offering a faster priority service for smaller parcels than other modes. Equally, as the capsules are smaller than rail consists or air cargo, small loads can be shipped at a more regular frequency further catering to services where time is the important factor. The report also suggests that due to the low operating costs, if the capital costs are shared between passengers and freight, there is an opportunity to keep freight costs lower and make Hyperloop more price competitive with rail and air freight.

The report also provides a high-level overview of capital costs and operating costs along the route, suggesting that construction costs could be between $50 and $75 Million USD per mile, depending on the scenario. These cost estimates are high level but limited detail provided is in the report to support them. They are, however, significantly higher than the cost per mile proposed in earlier Hyperloop studies.

**Status:** This study, referred to as the Great Lakes Hyperloop, is the largest collaboration of private and public organizations working with a Hyperloop company to develop a system in the United States. The study pulls together data from a variety of sources to inform its assessment and model runs.

Overall results suggest Hyperloop offers the opportunity to create some benefits for the Chicago to Cleveland and Pittsburgh corridor, and that it could also help alleviate existing congestion in the study area. Although the study considers a number of data sources, the details of the analysis provided in the report are limited, making the validity of the claims difficult to confirm. It is also noted there is little to no acknowledgment of the technological advances that could be made in other modes during the timescales of the study, for example, the change of power source for the automotive sector from combustion to electric engines is neither acknowledged nor even considered.
The study also fails to consider how changing land uses and social behaviours could impact future forecasting. Many urban areas are already seeing significant changes in the usage and design of places and spaces. At the same time, globally, a growing proportion of the younger generation is choosing not to drive.

The report adds some important context to the benefits that Hyperloop could offer. However, in order to fully assess the application of such a service, a more comprehensive study considering the true timescales for implementation of such a system and the changes occurring in land use planning, transportation technology, and other facets of society needs to be undertaken in order to truly understand the impact a Hyperloop system could have.
Engineering Design


**Publisher:** Princeton University

**Link:** Academic Paper: A Top-Down Systems Eng Evaluation of the Tech & Econ Feasibility

**Details:** The thesis opens with the original Hyperloop concept (Musk, 2013) and the characteristics of the system, including the propulsion of the capsules, the vacuum pumps, and the route itself. Analyses are provided on components, such as aerodynamics, propulsion, suspension, the compressor, and the route, among others. Some of this analysis utilized MATLAB modelling to provide explanations and evidence for the various technology components being considered. Analysis of infrastructure design and anticipated costs was also conducted, covering aspects such as the cost alterations related to different capsules and tube design. Revised cost estimates were used to assess the price of the original proposed route from Los Angeles to San Francisco, putting the cost closer to $16.84 Billion USD, with a significant proportion being due to the construction of the pylons that the tube would sit on ($7.65 Billion USD). This total cost is significantly more than the original price suggested by Musk and is based on the ongoing refinement and design of the technology solution.

**Engineering & Design:** Results for the analysis section of the thesis, which makes up most of the document, are outlined under each individual component (e.g. aerodynamic, propulsion, etc.). The authors noted much of the research is based on models that are only as good as the assumptions used when creating them. For example, when developing the model for drag, three assumptions were used, limiting comparability to real-world scenarios. The article also concluded that Hyperloop appears to be a better transportation mode than high-speed rail, with the primary reasons being the lower cost per mile to construct and anticipated lower per person operating costs.

**Status:** The thesis provides a detailed outline of the many different components of Hyperloop system and discussed the various limitations and assumptions of the evaluation process, such as those of the model described in the study. It acknowledges that many of the sources reviewed did not provide evidence or support for their claims. The thesis begins to unpack some of the complications and additional considerations along a proposed corridor that may have been overlooked and/or not given the same level of attention or acknowledgment in Musk’s Alpha paper.

**Title:** Article: Study on Model-based Hazard Identification for the Hyperloop System (2015), Zhao, D., Xin, W., Hessami, A., Wang, H.

**Publisher:** Atlantis Press

**Link:** Article: Study on Model-based Hazard Identification for the Hyperloop System

**Details:** The article begins with a brief introduction of the Hyperloop system, acknowledging the challenges and risks and including the need to prioritize safety.
The study then explains how the hazards associated with the Hyperloop system are determined using the model-based HAZOP (hazard and operability study) method, noting that since Hyperloop is a new technology it is important to increase public awareness of the technology and demonstrate how the system is addressing safety concerns.

The study uses four different modelling approaches to assess the safety of the Hyperloop system. The use of multiple models offers benefits such as an improved representation of the system, as well as capturing different expert opinions and approaches to hazard identification. The study establishes that while there are benefits to a method that utilizes multiple models, such as showing a dynamic system approach, there are also limitations. These include the challenges inherent in understanding the different models and the need for a cross-cutting, holistic appreciation of the wider system.

**Engineering & Design:** Although the primary focus of the paper was assessing the successful application of a multi-model approach to hazard identification, it did help to provide consensus regarding some of the most important hazard concerns for Hyperloop. The HAZOP method identified that energy storage by batteries, power supply for the propulsion system, power supply for the vacuum system, life support systems, and security were among the most significant risks the system faced.

**Status:** The findings presented in this article are important as they provide insight into some of the challenges that the Hyperloop system could offer in terms of risk. As the paper was developed in 2015, limited information existed and much of the assessment has been based on the original Alpha paper. This means that many of the risks identified have now been mitigated through innovation or are no longer applicable as new approaches have been developed. However, the paper does set out several concepts such as power supply to critical systems, such as capsule propulsion and life support systems, that are still applicable.

**Details:** The article begins with a brief overview of the history of the concept, noting examples from Boris Weinberg, the vactrain, evacuated tube transport, and Hyperloop before introducing TransPod’s model. The article explains how TransPod’s levitation solution uses magneto-dynamic levitation, propulsion, and a Linear Induction Motor (LIM) in the capsule system. Various forces and their impacts on the tube are defined, ranging from aerodynamics to propulsion to wind forces.

The Kantrowitz Limit is acknowledged, explaining the reason for the maximum velocity flow, and how a TransPod vehicle called M2A has a compressor and a nozzle that increases aerodynamics. On the same topic, it was determined that the safety components should have a long reaction time as a result of a Computational Fluid Dynamics (CFD) analysis.
The general characteristics of the tubes were described and the various methods used, such as the Physical-Fourier-Amplitude (PFA), which displays information in a heat map format for improved analysis.

**Engineering & Design:** The report summarises the proposed solution TransPod is developing and acknowledges there is still a lot of work to complete, identified by the various examples provided throughout the article of work to be done, such as the refinement of real-time sensor technology. These examples are supported by either TransPod-specific examples, technical documents, or noted Hyperloop studies. A number of findings throughout the body of the article, such as the computational fluid dynamics analysis, appeared to be unsubstantiated.

**Status:** The context of this article is technically-focused on the TransPod system and, as such, is specific to their design. The article’s main focus is to demonstrate the concept for Hyperloop that TransPod has developed and to identify some of the justification for the various design decisions they have taken in developing their system.

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**Title:** Academic Paper: MIT Hyperloop Final Report (2017), MIT Hyperloop Team

**Publisher:** Massachusetts Institute of Technology

**Link:** Academic Paper: MIT Hyperloop Final Report

**Details:** This report gives an overview of the Hyperloop concept and the subsequent student competition run by SpaceX for creating a pod design. It details the team from MIT that entered the competition and their achievements. The process for designing the pod is explained, outlining the technical considerations and tools used. The specifics of the levitation component are presented, including the reasoning for selecting Electrodynamics Suspension (EDS), the simulations used in developing the component, and how the pod would use physical skis for guidance along the track. The next section discusses the dynamics and external structure of the pod, the electronic elements, and the software used. The report then focuses on the testing that occurred and how it differed for the various components, such as using a rotary vs linear rig. Feedback from the SpaceX competition is summarized, including the many tests that took place at the event. The report closes with an overview of the competition data, including the acceleration performance of the pod.

**Engineering & Design:** Significant detail is provided on an array of technical design challenges the team had to overcome in developing their pod. This included considering how the pod runs along the tube and the best way to optimize the stability of the pod in the tube. Not only does the report detail solutions to the various challenges such as how the design and application of suspension between pod and ski can withstand the high speeds, but also details the process undertaken to reach a preferred solution. It also describes the extension modelling, and subsequent wind tunnel testing the team ran in order to optimize their pod design and minimize friction, whilst allowing sufficient air to pass the pod and avoid a pressure build-up.

**Status:** The findings of this report explain the reasoning for the design in terms of topics from levitation to electronics to software. These findings are based on models, simulations, and reference to other sources of
information. Overall, the report on MIT’s design for the competition is detailed and comprehensive, attempting to build on past studies, while noting how their process is different from those that previously used OpenMDAO.

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<td>Publisher: The National Aeronautics and Space Administration (NASA)</td>
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<td>Link: Study: Conceptual Feasibility Study of the Hyperloop Vehicle for Next-Gen Transport</td>
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**Details:** The article provides an overview of the components of a Hyperloop system before presenting the research questions of cost in relation to MagLev and high-speed rail and the implications of changing the size of the pod. It then discusses the use of the OpenMDAO model, outlining considerations such as cost, pod design (including components such as drag, pod shape, and levitation) and the tube (consisting of the vacuum, temperature, and propulsion). The analysis conducted assessed the distribution of the system in relation to the surface it is on (land vs underwater) the weight of the pod, and the ability to run multiple pods at once.

The results outline findings such as the higher the Mach number, the higher the cost, and that in any of the designs it is expected there will be some level of air leakage present, which will also have a cost consideration. The article concludes by summarizing the results and noting that the model is open-sourced, this being the primary source for many of the findings and assumptions provided.

**Engineering & Design:** Findings obtained by modelling a variety of designs and pod sizes found the energy costs and theoretical speeds did not significantly alter, suggesting that the system can operate with a wide range of passenger loads without significant change in operating expenses. The study also establishes, through the use of a high-level sizing study simulating variations in tube area, pressure, pod speed, and passenger capacity, that there is an optimal tube pressure, which minimizes operating energy usage, although this will be dependent on the pod and system design. The paper goes on to find that the combined estimates of energy consumption, passenger throughput, and mission analyses all support Hyperloop as a faster and cheaper alternative to short-haul flights and high-speed rail.

**Status:** Overall, the references consisted of academic articles and studies on Hyperloop along with technical papers. The data used to support model development is also considered to be sourced from the best available locations. The result identifies several interesting factors, including the benefits an underwater environment would have on the design and operating of the tube. Equally, the need to find a balance in energy consumption between pods propulsion and the low-pressure tube environment highlights the importance of a well-designed tube that minimizes leaks. The model constructed and the research results suggest that Hyperloop is viable as a new technology concept; although in making the model open source, the authors acknowledge the opportunity and need to build on their initial research.
Details: A brief overview of the Hyperloop system is provided before explaining that acceleration, deceleration, and cornering will be examined in relation to passengers. The methodology used is described, noting that Mathematical Dynamic Model (MADYMO) was used for modelling the different seats and seat belts designed for use within the Hyperloop. This was then applied to the three different test conditions of A, B, and C (Slower Acceleration – Tesla Branded Pod, Rapid Acceleration-Hyperloop Top Speed, and Worst-Case, respectively). The reasoning and descriptions for each of the test scenarios are outlined, along with the specifics for the dummy model (two types in total), reclining of the seat (three types in total), and seat belts (four types in total). The results of the model are outlined in detail through descriptions, figures, and summary tables. It is noted that different test conditions may cause different types or severity of injuries, such as head and pelvic injuries. Overall, the best option was the seat with both the reclined back and floor and the “four-point” seat belt. A Kriging Model (a regression model based on analysis interpolation and covariance data sets) was used, and the process for developing this was outlined. The last section of the thesis outlines the final findings from the study and provides the recommendations described below.

Engineering & Design: The results of this thesis were specific to the different injuries, seats, and seat belts tested. For instance, some examples noted that injuries were severe if no seat belts were used during deceleration or cornering, and two different seats were both identified to have similar results for acceleration.

As mentioned in the summary description provided, the best option was the seat with both the reclined back and floor (referred to as “Configuration-III”) and the “four-point” seat belt. The recommendations included items such as studying other velocities, materials, and types of seat belts along with creating a new ADAMS model. As the modelling work conducted was the focus of the thesis, the main results determined are only as good or accurate as the assumptions on which the work is based.

Status: The thesis “Effects of Acceleration, deceleration, and cornering on occupants inside a Hyperloop capsule/pod at Supersonic Velocities” is supported by various references. The literature review provided focuses on transportation mode-related injuries. It is also stated at the start of the thesis that this topic was chosen because not many studies examined these considerations. The references used throughout include academic studies, technical papers, and news sources, among others. While the use of various references and reasons for the study topic are commendable, the assumptions used for the models would need to be examined to determine the reliability of the results. In theory, once the validity of the results is determined, this thesis has the potential to play an important role in the safety consideration research for Hyperloop. It attempts to build on other research and apply it to the context of Hyperloop and may be a source that other articles could use or acknowledge in the future.
Details: The article gives an outline of the SpaceX competition which invited competitors to submit pod designs and to assesses whether the pod could complete the 1.6km test track and what the top speed achieved could be. The competition included pods that had been designed and entered by teams of students, including Water-loop from the University of Waterloo.

It discusses how a key component of the competition was the requirement to track the pod along the route, and also describes the various software developed for this task, starting with the embedded components. The embedded components used sensors to gather data, such as tracking the temperature of brakes as well as the current of the batteries. In addition, it also released commands, using CAN-BUS as well as both Master and Hub Units. The control component is discussed, outlining the different network examples compared in discussing how the control panel will receive the data. The importance of the launch script, allowing the pod to initiate movement is explained, outlining how, for this example, more than one Master Unit was utilized in case of a network shut down. The last part of this component discussed the integration of a Watcher Unit to be used for braking in emergencies. Navigation was also described, along with some of the issues with using other examples, such as coloured stripes inside the testing tube. The report then summarised the results of the tests in the last section.

Engineering & Design: One of the findings noted emergency braking could occur because of the CAN-BUS challenges but postulated that use of the quicker Ethernet would likely not be feasible as it is beyond the capacity of the current design. Additionally, the article acknowledges how the design would need to be altered to accommodate multiple pods following one another, given the braking system's current design limitations.

Status: The objective of the paper was to review the challenges occurring throughout the tested example. This included discussion of the different system components; implementing navigation for the pod; reasons for the various software used, for example, cheap to buy or easy to access; and the use of specific components, for instance, QUIC when transmitting data, by explaining issues such as speed of data transmissions with other options.

Overall, this article provides some context for the design used in the competition, noting how the design performed, and possible opportunities for use by technology developers.
Details: The thesis opens with the original Hyperloop concept before jumping into descriptions of various forms of suspension. A mechanical system, consisting of an axle and a wheel, is outlined along with its benefits and limitations. Then, aerodynamic systems, consisting of air bearings, are described while noting the Kantrowitz Limit as a potential constraint. Lastly, electromagnetic systems are outlined and noted to be costly. They are then explained in more detail, noting MagLev and how it could be applied to Hyperloop. The three ratios of lift over drag force (LDR), lift over power (LPR), and lift over weight (LWR) are also noted. Passive MagLev is outlined, noting that it is comprised of a surface that is conductive and permanently magnetic.

The implications of factors such as the Halbach Array, forces, and lost power are outlined, all of which are applied to various equations. Possible improvements are acknowledged, noting that certain tracks can lower skin-depth and altering magnet sizes in regard to the Halbach Array. Next, active MagLev is outlined, noting that it is comprised of a surface that is conductive and permanently magnetic, along with greater levitation control. The next section explains the simulations that were completed for active and passive MagLev through MATLAB, with results outlined and summarized at the end of the thesis.

Engineering & Design: One of the findings from this thesis was that the time for which the system is running and the force of lift applied is inversely related, noting that this is based on simulations conducted. The author noted that the modelling completed for active MagLev had some error plots, which highlighted its limitations.

Status: One of the main findings emerging from this article was that, while Hyperloop could use electromagnetic suspension, it would need to be tailored for this function and there are many other design considerations still to be addressed, such as stress variance and dynamic weight balancing. The report acknowledges that active MagLev is expected to be more efficient and allow for higher speeds to be realized, compared to alternatives such as wheels or air cushion systems.

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Details: The article describes the concept of MagLev, noting the different types: electromagnetic suspension (EMS), which is expensive and complex, and electrodynamic suspension (EDS), which has speed requirements but can run on its own. The article explains it will review both the linear synchronous motor (LSM) and EDS together to see if wheels are still required. Next, the characteristics of the study are outlined, including the “test branch” (which includes a pod and track), the Halbach Array that used eight magnetics, the dimensions and the number of coils used when constructing the model track, and the components of the control sensor. It notes that the Kalman filter is critical in this study because it compares the levitation coils and pod locations, before explaining various equations.
**Engineering & Design:** When conducting simulations, the report described how the pod would be unable to levitate due to energy restrictions and how the force lessens due to weak points (referred to as “flux leakage”). Testing of the various options included the construction of small sections of the test track in order to test the various designs. In reviewing the technologies, the researchers are able to establish a sufficient force to provide proof of concept through their developed prototype.

**Status:** The main finding of the article appears to be that the proposed method could be viable. However, it should be noted that the results of the article are not clear, and this result needed to be inferred to an extent. For example, the introduction explains the study was looking at both LSM and EDS together, but only briefly mentions this again in the conclusion. In addition, the limitations of the study are explained noting the restricted energy that had to be used due to having to use an inverter and the alterations that need to be done to generate results.

### Article: Hyperloop as an evolution of MagLev (2018), Santangelo, A.

**Publisher:** Transportation Systems and Technology

**Link:** Article: Hyperloop as an evolution of MagLev

**Detail:** The article starts by outlining the original concept of the Hyperloop Alpha paper and noting the previous work conducted by Boris Weinberg on a similar concept. It introduces MagLev, explaining how it differs from standard rail transportation and that there are differences in the magnets within Electromagnetic (EMS) and Electrodynamic Suspension (EDS). The concept of Inductrack is illustrated, which would use EDS, along with the way in which Hyperloop would be able to travel quicker than other transportation modes. Next, the tubes are reviewed in relation to factors such as curves, braking, and temperature considerations. Other items, such as expansion joints (in relation to temperature) and requirements for the substructures (for the foundation), are also examined. The next section looks at materials, noting the challenges of assessing stiffness, and described the properties of concrete, steel, composites, and hybrids. For instance, the structures for the tubes may be susceptible to leaks if concrete were used. Finally, the dynamics for Hyperloop are reviewed, noting that the closest comparison is from a set of guidelines for trains that go up to 450km/h. It introduces the Dynamic Amplification Factor (DAF), which is related to bridge deflection, as well as seismic isolation in the context of earthquakes.

**Engineering & Design:** The report aims to confirm the viability of some of the assumptions initially raised in Musk’s’ Alpha paper, to further prove the Hyperloop concept. This includes considering some of the possible construction materials such as concrete and steel. The paper considers the impact of aspects such as external wind factors and earthquakes on structural integrity, as well as a number of other environmental factors that could impact the system. The paper establishes that, based on the current level of Hyperloop development, the basic principles and environmental considerations are viable, however, the technology still needs further development and testing.
Status: The paper concludes by noting that Hyperloop has many considerations that still require examination. The article looks at the application of the MagLev design in the Hyperloop concept, acknowledging that the technologies are compatible, but that there would need to be a significant number of design amendments to the traditional MagLev design in order for it to operate within the Hyperloop environment.

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| **Title:** Academic paper: Aerodynamic Design of the Hyperloop Concept (2018), Opgenoord, M.M., Caplan, P.C
| **Publisher:** Massachusetts Institute of Technology
| **Link:** [Academic paper: Aerodynamic Design of the Hyperloop Concept](#) |

Details: The article describes the original concept from the Hyperloop Alpha paper, then outlines the design used by MIT in the SpaceX Hyperloop competition, noting which items were prioritized for the pod including the ability of the components to be applied to different scales, the easy building process that would be needed, and why electrodynamic suspension (EDS) was used for clearance of the tracks. The methodology of how the pod was designed is described, noting the considerations when determining the size due to requirements, the use of MTFLOW vs 3D Navier-Stokes CFD for analyses of flow due to cost, and comparisons between the shape of the pod throughout different stages of the design process. Further, the design of the pod is outlined from an aerodynamic perspective. The Kantrowitz limit is explained along with its impact on flow, noting that it was outside of the scope of the competition to implement the required infrastructure to accommodate for the impact. The location where the dummy person would be in the pod impacted the design along with the height of the tail in relation to drag, and configuration of the nose. The design was then put into a simulation and tested at Hyperloop speeds, focusing on the flow in relation to the shape of the pod, noting drag, pressure, and relation to the Kantrowitz Limit. Lastly, the conclusions of the article are discussed.

Engineering & Design: The main findings of this article concern how the different components of the pod's design were determined using simulations. As described, this included examining parts such as the tail and how the flow would be impacted by different variations.

It should be noted that the results of these findings are based on assumptions used for the simulations, such as using the same Reynolds number as provided in the Hyperloop Alpha paper, as well as determining the dummy person would be 3 ft when the competition regulations did not give a height. As such, the reliability of the simulations would need to be assessed in relation to the assumptions provided. In addition, it was noted that implementing a compressor would probably not save energy in relation to the Kantrowitz Limit. This finding is based on the final simulations that were run, along with comparing these findings in relation to the Hyperloop Alpha paper and an academic article on Hyperloop.

Status: This article does not appear to have any single main claim or finding regarding Hyperloop but rather explains the design used for the competition. The article’s reasonings were well-laid out throughout the report, for example explaining that the building process would need to be easy due to the short timeline.
This article focuses on the academic requirements for the design, which, although applicable to commercial use, are not necessarily considerate of the scale and costings a commercial system might want to employ.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Publisher: Korea National University of Transportation, Department of Electrical Engineering, Hanyang University</td>
</tr>
<tr>
<td></td>
<td>Link: <a href="#">Academic Paper: A study of non-symmetric double-sided linear induction motor</a></td>
</tr>
</tbody>
</table>

**Details:** This academic paper proposes an all-in-one system for Hyperloop that conducts propulsion, levitation and guidance.

Currently, the demand for high-speed long-distance transportation is increasing; this has resulted in significant attention being given to Hyperloop by various entities around the world. Hyperloop needs functions of propulsion, levitation, and guidance for its service and many devices are necessary for those functions. The tube is a constrained space where many devices make the entire system complicated, and the size of the vehicle and tube further increase the complexity. The costs of maintenance, manufacture and construction are increased, and control of each device becomes very difficult.

**Engineering & Design:** Non-symmetric double-sided linear induction motor (NSDLIM) is an all-in-one system that could conduct all functions. Requirements of NSDLIM were investigated considering very high acceleration, velocity, and low air pressure. This model was designed and analyzed using the finite element method. NSDLIM parameters that affect performance were investigated and adjusted to improve performance.

NSDLIM has a structure similar to the single-sided linear induction motor – a double-sided primary is installed on the bottom of the tube and a secondary plate is attached under the bottom of the vehicle; this could perform propulsion, levitation, and guidance all in one. The travelling magnetic field from the primary effects the secondary reaction plate which causes an eddy induced in the reaction plate by the change of the magnetic field. The eddy current produces both directional force and vertical force.

**Status:** The paper provides a technical review of the feasibility and design complexities of the use of the linear motor concept in the pod design to provide propulsion and levitation. The findings show that it is feasible to create levitation for the pod using an induction motor; however, the weight of the pod becomes a critical factor in the required force to generate sufficient levitation.
APPENDIX

HYPERLOOP TECHNOLOGY QUESTIONNAIRE
Appendix C

Appendix C – Hyperloop Concept and Engineering Design Q&A

Why is capsule capacity constrained to 28-40 passengers?

This is by no means a hard constraint and the range of capsule capacities currently being developed is 20-100 according to the questions posed by this study to Hyperloop developers. The main reasoning behind Hyperloop’s small vehicles (compared to air and rail travel) is to allow for fast on-demand travel, with passengers departing minutes after arriving at the station. Thus, when demand is lower, energy is not wasted transporting large and mostly empty vehicles. When demand is at its peak, on the other hand, several vehicles can be coupled to multiply the system’s capacity. Answers to the questionnaire indicate vehicle coupling will be possible on all Hyperloop systems. For more information, see Section 3.2.8 Error! Reference source not found.- Operations.

A further benefit of smaller, more frequent vehicles is the resulting smaller, less expensive infrastructure. The tube’s diameter and rigidity can be decreased as vehicles become smaller and lighter, respectively. Moreover, even though smaller vehicles actually increase the energy consumption per passenger, the footprint and cost of the necessary infrastructure to deliver this energy is reduced. For more information, see Section 3.2.1 and 3.2.2 - Infrastructure.

If capsules slow down in dense urban centres, would this require longer departure headways?

The short answer is that if all vehicles have to slow down equally, then no, headways are not affected. If, on the other hand, it is desired that some vehicles slow down while others do not, then a longer departure headway is required for the faster vehicle.

Whether the vehicles will have to slow down in dense urban centres is up to the regulators in each country, but it may be possible to limit the noise generated by a Hyperloop system such that daytime noise pollution targets of under 55 dB in residential areas are met even at top speed. This very much depends on the system configuration, see Section 3.2.9 Audible and Electromagnetic Noise for more information.

In the event of a situation where the tubes are significantly re-pressurised, requiring the system to shut down, what is the travel time necessary for wheel deployed capsules to evacuate passengers to the next station?

This is simply a function of evacuation speed and distance to the nearest station. Since the distance to the station will vary case-to-case, but evacuation speed will not, this answer will focus on the latter. The worst-case scenario for evacuation speed is a system with intermittent propulsion that coasts between two propulsion sections, where the vehicle in question is stopped while coasting. In this case, the vehicle would deploy its emergency on-board propulsion, which may be implemented through wheels. Using existing
MagLev systems as a case study, the speed achieved by this wheeled propulsion under atmospheric pressure is likely to be 50-100 km/h. In a scenario where a vehicle is stopped in between stations, consideration to the provision of alternative evacuation points would be required. This could take the form of evacuation shoots that provide passenger access to ground level and subsequent collection by ground-based vehicles.

However, it is more likely that vehicles will carry alternative on-board propulsion, an axial compressor and/or a linear induction motor, except in the event they run on infrastructure-side propulsion. In these cases, evacuation times could be decreased to tens of minutes, even at atmospheric pressure, with speed limited by the blockage ratio rather than the propulsion technology. Refer to Section – 3.2.3 and 3.2.4 Propulsion and Power Delivery for further detail. Furthermore, several Hyperloop companies have stated that evacuations will not only take place at stations, but that infrastructure would include additional emergency stops with open-air access, safety exit diversions, or walkways designed in line with existing tunnel and metro evacuation protocols. As such, evacuation time could be reduced to no more than a few minutes.

In the event of a significant re-pressurisation leak, emergency braking would halt all capsule movement, and travel to the nearest station would be completed at lower speeds. How long could the capsule maintain passenger life support systems, for both respiration and cooling?

In the worst-case scenario, where on a hot day the tube is only partially re-pressurised such that the air inside is still not suitable for breathing, conditions may be roughly comparable to those of an aircraft. Literature on fully electrified environmental control systems (pressurisation, respiration and cooling) for aircraft estimate a worst-case power consumption of 1.5 kW per passenger. In other words, 1.5 kWh of battery capacity is needed to sustain one passenger for one hour. Hence, a Tesla Model S sized battery (100 kWh) coupled with a 30-passenger vehicle could maintain life support systems and low speed wheeled travel (assuming a 100 kW propulsion, equivalent to an average car at full power) for around 41 minutes - or for 133 minutes without using on-board propulsion. Ultimately, the size of the battery capacity and power rating of the emergency propulsion are chosen such that life support systems can be operated for a sufficient time.

However, unlike with road and (most) rail tunnels, there is no risk from fumes in Hyperloop tubes. So, if a tube were to re-pressurise to atmospheric pressure, there would be no immediate need for an active respiration system - at this point, the conditions in the Hyperloop vehicle are not much different from those of a train, as the pumps that normally maintain vacuum could be used to create air flow. Should an emergency evacuation scenario occur, due to a leak or otherwise, it would be sensible to re-pressurise the tube to a full atmosphere - this would be done by controlling vacuum pumps / valves and hence would not consume the vehicle’s on-board resources. The only required life support system, then, is cooling at roughly 0.5 kW per passenger16 - this could be maintained for 54 minutes with the same battery and emergency propulsion as before, or for well over six (6) hours without propulsion. Minding that it is possible for passengers to evacuate at various emergency points between stations, the time duration capacity of life support systems is not considered an issue.
An estimated 4000kg of batteries is needed for 45 minutes of travel time and it was indicated that these would be changed at stations. If battery capacity, with a safety margin, is not great enough to complete a trip and batteries need to be changed mid-trip, do passengers need to change capsules or can this be done at the platform? What would the delay be?

No passenger transport system with battery swapping technology has been implemented in the past so the time delay is difficult to estimate with any confidence, but there is no reason this could not be done with passengers still on-board. If passengers simply change to a different vehicle, then the maximum additional time spent not travelling would be the headway plus the time it takes passengers to transfer and board - perhaps 5 minutes total. However the passengers incur further delays as the vehicles decelerate, stop and re-accelerate for the mid-trip battery swap. This is time that could have otherwise been spent travelling at full speed - this accounts for a further four (4) minute delay at a top speed of 250 m/s and acceleration capped at 0.1 G.

However, changing batteries mid-trip is considered impractical and even if capacity cannot be increased further, other measures would be taken first to extend the journey time - these may include decreasing acceleration and/or speed, transferring energy to the vehicle through solar or alternative fuel sources, or propelling the vehicles in a manner not reliant on on-board energy sources. See Section 3.2.3 and 3.2.4 Propulsion and Power Delivery for further detail.
APPENDIX
QUESTIONNAIRE RESPONSES
# Appendix D

## Appendix D – Key Questionnaire Responses from Hyperloop Developers

<table>
<thead>
<tr>
<th>Discussion Items</th>
<th>Range of Answers</th>
<th>Weighted Average / most common answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time until the technology available for public use</td>
<td>5 - 15 years</td>
<td>10 years</td>
</tr>
<tr>
<td>Vehicle mass</td>
<td>9,000 - 30,000 kg</td>
<td>20,000 kg</td>
</tr>
<tr>
<td>Vehicle capacity</td>
<td>20 - 100 passengers</td>
<td>47 passengers</td>
</tr>
<tr>
<td>System capacity</td>
<td>2,000 - 20,000 passengers per hour</td>
<td>6,500 passengers per hour</td>
</tr>
<tr>
<td>Shortest operating headway</td>
<td>12 - 300 seconds</td>
<td>120 seconds</td>
</tr>
<tr>
<td>Maximum operating speed</td>
<td>700 - 1,200 km/h</td>
<td>900 km/h</td>
</tr>
<tr>
<td>Propulsion type</td>
<td>Infrastructure-side, vehicle-side, intermittent</td>
<td>Infrastructure-side, intermittent</td>
</tr>
<tr>
<td>Presence of an axial compressor</td>
<td>Yes, no</td>
<td>No</td>
</tr>
<tr>
<td>Levitation type</td>
<td>Active (permanent and electromagnets), passive (permanent magnets, superconductors)</td>
<td>Passive (permanent magnets)</td>
</tr>
<tr>
<td>Tube material</td>
<td>Steel, reinforced concrete, other</td>
<td>Steel</td>
</tr>
<tr>
<td>Requirements for additional electromagnetic shielding outside the tube</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Possibility to more than double system capacity through vehicle coupling</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Possibility of track switching at high speeds</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Public concerns</td>
<td>Service price, infrastructure cost, safety, comfort</td>
<td>Safety</td>
</tr>
<tr>
<td>Are vacuum pumps always on?</td>
<td>Only a small minority, no</td>
<td>Only a small minority</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>100 - 10,000 Pa</td>
<td>Insufficient data - typical assumption is around 100 Pa.</td>
</tr>
</tbody>
</table>
APPENDIX

HYPERLOOP TECHNOLOGY
COMPANY OVERVIEW
# Appendix E

## Appendix E: Hyperloop Technology Company Overview

<table>
<thead>
<tr>
<th>Company Location</th>
<th>TransPod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Founded in 2015 with headquarters in Toronto, Canada¹</td>
<td></td>
</tr>
<tr>
<td>3 Office Locations:</td>
<td></td>
</tr>
<tr>
<td>• Canada (Toronto), Italy (Bari), France (Limoges)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Published Information</th>
<th>Hyperloop Pre-Feasibility Study for Thailand (2019)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>• This study proposes that if the TransPod system was implemented within the Bangkok – Chiang Mai – Phuket Corridor there would be an economic rate of return of 13.78% for 5 years of construction and 30 years of operation and an increase in the gross domestic product of 4.7%. This system would also result in 184,000 jobs created, reduction in 1.2 million tonnes of carbon emissions per year, saving 200 million travel hours per year and reduction in road traffic fatalities of 16,000 casualties per year. TransPod presented these results with the leader of Thailand’s national Future Forward Party.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Cost Study for Hyperloop System in Toronto-to-Windsor corridor (2017)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>• This study proposes that if the TransPod system was implemented within the Toronto – Windsor corridor with multiple stops the system would cost half of the projected cost of high-speed rail along the same route and operate at four times the speed making the system more efficient.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TransPod Ultra-High-Speed Tube Transportation Dynamics of Vehicles and Infrastructure (2017)⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>• This study shows that TransPod seeks to improve the Hyperloop concept using electromagnetic propulsion of vehicles within a protected guideway whose air pressure is reduced and controlled for improved performance at high speeds. The TransPod tube environment is designed for levitation systems, stability systems and safety support systems to allow multiple TransPod vehicles to run simultaneously. Analysis of structural</td>
</tr>
</tbody>
</table>

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and aerodynamics, physical-fourier-amplitude-domain analysis, and machine-learning based vibration sensing and control was also completed based on system metrics.


- This study proposes the cost breakdown of three types of hyperloop guideway infrastructure (elevated, on-ground, underground). The initial order of magnitude analysis identified the preliminary capital cost for TransPods hyperloop system within the Toronto-Windsor corridor. With an initial cost of $29 M per km, this confirms that it is possible to build an affordable and faster service at 50% less than projected costs of the High-Speed Rail within the same corridor.

<table>
<thead>
<tr>
<th>Geographic Locations</th>
<th>TransPod example and possible routes: 6,7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canada</strong></td>
<td></td>
</tr>
<tr>
<td>Ontario, Toronto – Windsor (~370 km)</td>
<td></td>
</tr>
<tr>
<td>Ontario, Montreal – Ottawa – Toronto (~650 km)</td>
<td></td>
</tr>
<tr>
<td>Alberta, Calgary – Edmonton (~300 km)</td>
<td></td>
</tr>
<tr>
<td><strong>United States/ Canada</strong></td>
<td></td>
</tr>
<tr>
<td>Chicago – Detroit – Toronto (~850 km)</td>
<td></td>
</tr>
<tr>
<td>Vancouver – Seattle – Portland – San Francisco (~1550 km)</td>
<td></td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td></td>
</tr>
<tr>
<td>New York – Boston (~350 km)</td>
<td></td>
</tr>
<tr>
<td>Washington DC – Philadelphia – New York (~380 km)</td>
<td></td>
</tr>
<tr>
<td>Orlando – Miami (~390 km)</td>
<td></td>
</tr>
</tbody>
</table>

8. [https://www.google.ca/maps](https://www.google.ca/maps)
<table>
<thead>
<tr>
<th>TransPod</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dallas – Austin – San Antonio – Houston (~760 km)</strong></td>
</tr>
<tr>
<td><strong>Bangkok – Chiang Mai – Phuket Corridor (~850 km)</strong></td>
</tr>
<tr>
<td><strong>Bangkok – Kuala Lumpur (~1400 km)</strong></td>
</tr>
<tr>
<td><strong>Mecca – Riyadh (~870 km)</strong></td>
</tr>
<tr>
<td><strong>Adelaide – Melbourne – Canberra – Sydney – Brisbane (~4000 km)</strong></td>
</tr>
<tr>
<td><strong>Mexico City – Leon – Guadalajara (~625 km)</strong></td>
</tr>
<tr>
<td><strong>London – Birmingham – Manchester – Newcastle upon Tyne – Glasgow (~820 km)</strong></td>
</tr>
<tr>
<td><strong>Paris – Toulouse (~700 km)</strong></td>
</tr>
<tr>
<td><strong>Bordeaux – Toulouse – Montpellier (~500 km)</strong></td>
</tr>
<tr>
<td><strong>Paris – Frankfurt (~580 km)</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Press Articles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>October 2015</strong></td>
</tr>
<tr>
<td>• TransPod is founded. The team forms with a goal to design a 1000 km/hour hyperloop vehicle and system.</td>
</tr>
<tr>
<td><strong>April 2016</strong></td>
</tr>
<tr>
<td>• TransPod co-founder and CEO (Sebastian Gendron) speaks at TedXThunderBay about Hyperloop, the 5th Mode of Transportation on June 10th.</td>
</tr>
</tbody>
</table>

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### Press Articles

2016. He explains the concept and technology of hyperloop.

May 2016
- TransPod co-founder and CEO delivers a keynote speech at the World Congress Railway Research 2016 (Milan, Italy). He discusses benefits of the technology including environmental sustainability, speed, reliability and efficiency. He also presents the first half-scale prototype of the system produced by TransPod.

September 2016
- TransPod in partnership with CoeLux architectural and design firm, revealed the Hyperloop design and onboard experience at InnoTrans 2016 in Berlin, Germany with its first full-scale prototype.

October 2016
- CTO and co-founder (Ryan Janzen) to speak at CityAge Toronto: Build the Future Conference. The main theme of the event was to discuss opportunities and solutions to manage rapid urban growth in Southern Ontario. Janzen’s talk touched on the Montreal – Ottawa – Toronto corridor which sees 12 M people travelling regularly.

November 2016
- TransPod Announces 50 Million USD Seed Round Funding from Angelo Investments (Italian high-tech holding group specializing in advanced technologies for railway, space and aviation industries). The funding is intended for increased global growth of TransPod and producing a commercially viable product by 2020.

January 2017
- TransPod partners with IKOS (technology consulting firm) to design and develop Hyperloop Power System.

March 2017

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### Press Articles

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2017</td>
<td>TransPod partners with Liebherr-Aerospace (global supplier of air management, flight control actuation systems, landing gears and gearboxes) to develop Next-Generation Thermal Management Technology for Hyperloop.</td>
</tr>
<tr>
<td>July 2017</td>
<td>TransPod releases initial cost study for Hyperloop system in the Toronto-Windsor corridor. The study indicates that TransPod would cost half the projected cost of an HSR system within the same corridor.</td>
</tr>
</tbody>
</table>
| June 2018 | TransPod was unable to secure political support for technologies within Canada therefore testing begins in France. Transportation initiative by TransPod states that the system could be ready to carry passengers in the early 2030’s.  
A 10 km test track in Alberta could be ready by 2022 if TransPod wins provincial support, construction would begin in 2020. |
| June 2018 | Canadian and European hyperloop leaders launch an industry-first partnership to establish international standards and regulatory framework.  
The partnership includes TransPod, Hardt, Zeleros and Hyper Poland |
| February 2019 | |

### Press Articles

- TransPod expands the company footprint and partner network in France for the construction of test track and hyperloop system development. This included a 20m euro grant from the European Union\(^\text{19}\). The expansion includes a 3 km test track, the company plans to begin testing in 2020.

April 2019\(^\text{21}\)
- TransPod releases results of the Hyperloop Pre-Feasibility Study for Thailand, outlining the economic, environmental and human benefits of the system being implemented within the Bangkok – Chiang Mai – Phuket Corridor.

### Partnerships

TransPod has developed the following partnerships\(^\text{22,23}\):

**EDF**
- Major supplier of energy in a number of European markets and will provide energy for the Hyperloop facility in France.

**Arcelor Mittal**
- Supporting the development of new alloys for the use in Hyperloop tracks.

**La Sade**
- Are a construction firm with special interest in the communications sector.

**Blackshape Aircraft**
- Blackshape develops and produces high performance carbon fibre aircraft, for civil aviation and military training, focusing on innovation and quality.

**SITAEI**

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<table>
<thead>
<tr>
<th>Partnerships</th>
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<tbody>
<tr>
<td>SITAEI</td>
<td>designs, develops and produces innovative solutions for space and small satellites, industrial and scientific endeavours. They have worked on the Space Agency ATV, Mars Curiosity Rover, several research satellites and technology on the International Space Station.</td>
</tr>
<tr>
<td>MERMEC</td>
<td>designs and develops vehicles and measuring systems for railway infrastructure.</td>
</tr>
<tr>
<td>IKOS</td>
<td>is a leader in the railway industry, with more than 650 engineering consultants working on projects around the world.</td>
</tr>
<tr>
<td>REC Architecture</td>
<td>REC is a French architecture studio located in Toulouse and Paris that brings technical, creative and managerial expertise to develop major infrastructure projects around the globe.</td>
</tr>
<tr>
<td>Liebherr-Aerospace</td>
<td>develops leading edge technology for civil and military aircraft programs.</td>
</tr>
<tr>
<td>MaRS Discovery District</td>
<td>MaRS Discovery District located in Toronto, Canada is one of the world’s largest urban innovation hubs.</td>
</tr>
<tr>
<td>Autodesk Toronto Technology Center</td>
<td>The Autodesk Technology Center is a place for customers, partners, start-ups, academia and government organizations to push the boundaries of future technologies.</td>
</tr>
<tr>
<td><strong>Virgin Hyperloop One (VHO)</strong></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td></td>
</tr>
<tr>
<td><strong>Company Location</strong></td>
<td>Founded in June 2014, the VHO Innovation Campus is located within Los Angeles, California, USA. 24 The Apex Test and Safety Site is located within North Las Vegas, Nevada, USA. Regional VHO offices are in London and Dubai.</td>
</tr>
</tbody>
</table>
| **Published Information** | Feasibility Study for Virgin Hyperloop One Route through the I-70 corridor in Missouri, USA (2018) 25  
- The key findings of this study conclude that a hyperloop travel corridor located along the I-70 could connect Kansas City, St. Louis and Columbia. The trips would take 28 minutes and 15 minutes respectively using VHO technologies. Using VHO technology this would lead to an 80% increase in ridership demand from 16,000 to 51,000 riders per round trip. The VHO system would lead to savings from less time spent on the road ($410M USD/year) and reduction in accidents along the I-70 ($91M USD/year). Overall, VHO linear infrastructure costs are approximately 40% lower than high speed rail projects.  
Feasibility Study for VHO route between Pune and Mumbai in India (2018) 26  
- The study has limited information as it has now been cancelled, but it would have seen VHO partner with public sector bodies in India for the development of a test track that could have been developed into an entire route in the future.  
Pre-feasibility Hyperloop Analysis for Hyperloop Corridors Between Raleigh, Durham, Chapel Hill and RDU International Airport (2018) 27  
- The study considered connecting the research triangle in North Carolina using Hyperloop to offer faster trips between the different locations in the technology triangle. |
| **Geographic Locations** | Proposed winning routes based on the VHO Global Challenge (2016) 28:  
Canada  
- Toronto – Ottawa – Montreal (~650 km) |

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24 [https://hyperloop-one.com/facts-frequently-asked-questions](https://hyperloop-one.com/facts-frequently-asked-questions)  
28 [https://www.google.ca/maps](https://www.google.ca/maps)
**Virgin Hyperloop One (VHO)**

<table>
<thead>
<tr>
<th>Geographic Locations</th>
<th>United States</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cheyenne – Denver – Pueblo (~350 km)</td>
</tr>
<tr>
<td></td>
<td>o With stops at Fort Collins, Greeley, Longmont/Boulder, I-76, Denver International Airport, DTC, West Metro, Silverthorne/Dillon, Vail, Colorado Springs</td>
</tr>
<tr>
<td></td>
<td>Chicago – Columbus – Pittsburgh (~880 km)</td>
</tr>
<tr>
<td></td>
<td>Miami – Orlando (~390 km)</td>
</tr>
<tr>
<td></td>
<td>Dallas – Laredo – Huston (~1200 km)</td>
</tr>
<tr>
<td></td>
<td>o With stops at DFW Airport, Austin, and San Antonio</td>
</tr>
<tr>
<td></td>
<td>Mexico</td>
</tr>
<tr>
<td></td>
<td>Mexico City – Guadalajara (~625 km)</td>
</tr>
<tr>
<td></td>
<td>o With stops at Leon De Los Aldama and Queretaro</td>
</tr>
<tr>
<td></td>
<td>United Kingdom</td>
</tr>
<tr>
<td></td>
<td>Edinburgh – London (~650 km)</td>
</tr>
<tr>
<td></td>
<td>o With stops at Manchester and Birmingham</td>
</tr>
<tr>
<td></td>
<td>Glasgow to Liverpool (~360 km)</td>
</tr>
<tr>
<td></td>
<td>o With stops at Edinburgh, Newcastle upon Tyne, Leeds and Manchester</td>
</tr>
<tr>
<td></td>
<td>India</td>
</tr>
<tr>
<td></td>
<td>Bengaluru – Chennai (~350 km)</td>
</tr>
<tr>
<td></td>
<td>o With stops at Kolar, Palamaner, Chittoor and Kanchipuram</td>
</tr>
<tr>
<td></td>
<td>Mumbai – Chennai (~1340 km)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2016</td>
<td>Virgin Hyperloop One works towards making hyperloop a reality with successful propulsion testing and new partnerships with global infrastructure firms. The company announced the closing of an $80 M Series B financing with ongoing investments. The company also gained positive government support from North Las Vegas, Clark County, and the State of Nevada as officials were quick to see the potential Hyperloop One and were instrumental in development of the Las Vegas test site.</td>
</tr>
<tr>
<td>July 2016</td>
<td>Hyperloop One, FS Links and KPMG publish the first study of a full scale hyperloop system. The data from this study was presented at the Northern Lights business summit in Helsinki, Finland to reinforce the economic and social case for a 500-km hyperloop system linking Helsinki and Stockholm (at a cost of 19 B Euros). Based on the study’s findings the Salo, Finland has signed a Letter of Intent with Hyperloop One to become the first Hyperloop city along the proposed Helsinki-Stockholm route.</td>
</tr>
<tr>
<td>July 2016</td>
<td>Hyperloop One opens hyperloop one metalworks located in North Las Vegas, Nevada used in testing hyperloop technology.</td>
</tr>
<tr>
<td>August 2016</td>
<td>An Hyperloop One feasibility study is proposed to assess the business case for using Hyperloop One to move freight from container ships docked at Jebel Ali to a planned DP World inland container depot.</td>
</tr>
</tbody>
</table>

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### Virgin Hyperloop One (VHO)

#### Press Articles

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2017</td>
<td>- Hyperloop One announces $50M USD in new financing bringing the total to $160M USD.</td>
</tr>
<tr>
<td></td>
<td>- Hyperloop One makes history with the World’s first successful hyperloop full systems test located at the “DevLoop” track in Nevada (500 m).</td>
</tr>
<tr>
<td></td>
<td>- The pod uses electromagnetic propulsion and magnetic levitation and measured 28 feet long. The pod reached a top speed of 78 mph for the first phase of testing.</td>
</tr>
<tr>
<td></td>
<td>- Second phases of testing reached speeds up to 310 km/hr.</td>
</tr>
<tr>
<td>October 2017</td>
<td>- Hyperloop One and Virgin Group develop partnership to form Virgin Hyperloop One (VHO) and Richard Branson of Virgin Group has joined the Board of Hyperloop One.</td>
</tr>
<tr>
<td>January 2018</td>
<td>- A feasibility study for hyperloop project from Kansas City to St. Louis kicks off. The hyperloop route would run along the I-70 in Missouri.</td>
</tr>
<tr>
<td></td>
<td>- The study is conducted in partnership with Virgin Hyperloop One, University of Missouri and Black and Veatch.</td>
</tr>
<tr>
<td>February 2018</td>
<td>- VHO plans to address congestion in India’s corridor of Pune – Mumbai. The state of Maharashtra has announced intent to build a hyperloop system in agreement with VHO. The hyperloop route would link Pune, Navi Mumbai and Mumbai in approximately 25 minutes and would reduce greenhouse gasses by 150,000 tonnes annually.</td>
</tr>
<tr>
<td>May 2018</td>
<td>- Virgin Hyperloop One, Colorado Department of Transportation and AECOM conduct second half of feasibility study for a Virgin Hyperloop One project.</td>
</tr>
</tbody>
</table>

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36 [https://hyperloop-one.com/introducing-virgin-hyperloop-one](https://hyperloop-one.com/introducing-virgin-hyperloop-one)


Virgin Hyperloop One (VHO)

<table>
<thead>
<tr>
<th>Press Articles</th>
<th>portal located near the Denver International Airport.</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2018⁴⁰</td>
<td>Feasibility study conducted by VHO in partnership with government within the Pune – Mumbai corridor enters the advanced stages.</td>
</tr>
<tr>
<td>August 2018⁴¹</td>
<td>The Spanish government has signed a comprehensive deal to open the European Hyperloop development facility (valued at $500 M USD) in partnership with VHO.</td>
</tr>
<tr>
<td>March 2019⁴²</td>
<td>The NETT Council announces support for hyperloop commercialization and plans to explore regulations and permitting of the hyperloop technology.</td>
</tr>
<tr>
<td>June 2019⁴³</td>
<td>VHO presents hyperloop technology to potential state and federal partners in the USA and discuss potential routes throughout the USA. This meeting follows the formation of the Non-Traditional and Emerging Transportation Technology (NETT) Council.</td>
</tr>
<tr>
<td>July 2019⁴⁴,⁴⁵,⁴⁶,⁴⁷</td>
<td>Stakeholder’s (AECOM, VHO, North Carolina Regional Transportation Alliance) discuss the findings and implications of a pre-feasibility hyperloop analysis for hyperloop corridors between Raleigh, Durham, Chapel Hill and RDU international airport.</td>
</tr>
<tr>
<td></td>
<td>Virgin Hyperloop One and Saudi Arabia partner to build the World’s first long-range hyperloop test track.</td>
</tr>
</tbody>
</table>

| Press Articles | • VHO starts a road show to bring proposed hyperloop XP-1 pod to cities within the US including Columbus, Arlington and Kansas. This pod reached speeds of 240 mph in the 550-yard test track and integrated all components including use of an efficient motor, power electronics, magnetic levitation, vacuum pumping systems and an aerodynamic vehicle as a single system.  
  • The Government of Maharashtra has approved hyperloop as a public infrastructure project. The project plans to link Pune to Mumbai in 35 minutes.  
  • VHO and Saudi Arabia’s Economic City Authority plan to conduct a study to build the World’s longest test and certification hyperloop track located north of Jeddah that will be 35 km long. This will also include a research and development centre and a hyperloop manufacturing facility (Kitty Hawk). January 2020⁴⁸  
    • Virgin Hyperloop One announces that the technology can be powered completely off-grid for plans in the Middle East. February 2020⁴⁹  
  • The Ministry of Transport of Saudi Arabia has announced in contract with WHO to conduct a pre-feasibility study on the use of Hyperloop technology for passenger and cargo transport throughout Saudi Arabia including potential routes, expected demand, cost and socio-economic benefits. |
|---|---|

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<table>
<thead>
<tr>
<th>Company Location</th>
<th>Founded in 2013[^1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTT has opened five office locations:</td>
<td></td>
</tr>
<tr>
<td>• Los Angeles, California, USA</td>
<td></td>
</tr>
<tr>
<td>• Sao Paulo, Brazil</td>
<td></td>
</tr>
<tr>
<td>• Barcelona, Spain</td>
<td></td>
</tr>
<tr>
<td>• Toulouse, France</td>
<td></td>
</tr>
<tr>
<td>• Dubai, UAE</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Published Information</th>
<th>There are currently 11 on-going Global projects undertaken by Hyperloop TT and partners[^2]:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abu Dhabi, UAE</strong> – Commercial Passenger System (5 km)</td>
<td></td>
</tr>
<tr>
<td>• Agreements between Government Officials and Aldar Properties have been made to provide HTT transportation between Abu Dhabi and Al Ain.</td>
<td></td>
</tr>
<tr>
<td>• Construction Target to begin in Q1 of 2020</td>
<td></td>
</tr>
<tr>
<td><strong>Great Lakes, United States – Feasibility Study</strong></td>
<td></td>
</tr>
<tr>
<td>• In partnership with Northeast Ohio Areawide Coordinating Agency, HTT plans to facilitate a feasibility study to connect Cleveland, Chicago and Pittsburgh and will eventually lead to a consortium of routes throughout the Great Lakes Region.</td>
<td></td>
</tr>
<tr>
<td><strong>Toulouse, France – R&amp;D Center and Full-Scale Prototype Testing</strong></td>
<td></td>
</tr>
<tr>
<td>• This site will act as the staging grounds for commercial projects. The Facility will be designed to develop and test hyperloop and related technologies.</td>
<td></td>
</tr>
<tr>
<td><strong>Tongren, China – Commercial Passenger System</strong></td>
<td></td>
</tr>
<tr>
<td>• Agreements have been signed to build a 10 km commercial Hyperloop system in Tongren, China.</td>
<td></td>
</tr>
</tbody>
</table>

[^1]: [https://www.hyperlooptt.com/about-us](https://www.hyperlooptt.com/about-us)
[^2]: [https://www.hyperlooptt.com/]
<table>
<thead>
<tr>
<th>Published Information</th>
<th>Hyperloop Transportation Technologies (HTT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhra Pradesh, India – Feasibility Study</td>
<td>Agreements have been made with the Government of Andhra Pradesh to connect the city centers of Amaravati and Vijayawada using HTT. The pre-feasibility study for this project has been completed.</td>
</tr>
<tr>
<td>South Korea – R&amp;D Collaboration</td>
<td>Agreements between HTT and the Korea Institute of Civil Engineering and Building Technology and Hanyang University are in place to co-develop a hyperloop system (Hypertube Express, HTX) in South Korea.</td>
</tr>
<tr>
<td>Jakarta, Indonesia – Feasibility Study</td>
<td>Agreements to begin a feasibility study to use HTT within Indonesia (focused on Jakarta).</td>
</tr>
<tr>
<td>Brno, Czech Republic – Feasibility Study</td>
<td>Agreement to begin a feasibility study for a hyperloop system that connects Brno, Czech Republic – Bratislava, Slovakia – Prague, Czech Republic.</td>
</tr>
<tr>
<td>Kiev, Ukraine – Commercial Passenger System</td>
<td>HTT and the Ministry of Infrastructure in Ukraine plan the first commercial system and regulatory framework for Europe. The system will be composed of a 10 km track and later be extended.</td>
</tr>
<tr>
<td>Hamburg, Germany – Joint Venture Cargo</td>
<td>Agreement between HTT and HHLA (Port of Hamburg operator) to use HTT and innovation to solve shipping industry issues in Germany.</td>
</tr>
</tbody>
</table>
| Geographic Locations | Hyperloop Transportation Technologies (HTT) has signed agreements in the following locations to explore possible routes and options:

- China (Guizhou Province)
- United States (Great Lakes Chicago – Cleveland – Pittsburgh)
- UAE
- India
- Brazil
- France
- Slovakia
- Czech Republic
- Indonesia
- Korea
- Ukraine |
| Press Articles | December 2018
- Hyperloop Transportation Technologies and HHLA form a new joint venture to solve shipping industry challenges in Germany.
- Proposal for an initial study on connecting a cargo-based hyperloop system from HHLA container terminal to container yards located further inland in order to expand the ports capacity and reduce congestion within neighbouring Cities (Hamburg, Germany).

February 2018
- Hyperloop Transport Technologies and NOACA expand the Cleveland to Chicago project with regional organizations. |

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### Hyperloop Transportation Technologies (HTT)

#### Press Articles

- **October 2018**[^56]
  - $1.2M USD is invested for feasibility study in the Great Lakes area megaregion in partnership with the Great Lakes Hyperloop Consortium.
  - Hyperloop Transportation Technologies begins construction on World’s first full-scale passenger and freight system.
  - Plans for the research and development facility are to take place in Toulouse, France.
  - The pod has an interior diameter of 4 m and the system was optimized for both passenger capsules and shipping containers. The total length of the system is 320 m and a second full-scale 1 km system that is elevated on 5 m pylons (to be completed in 2019).

- **April 2018**[^57]
  - Hyperloop Transportation Technologies moves forward with the first commercial hyperloop system in the UAE.
  - In partnership with Aldar properties, the prospect for a commercial hyperloop system of 10 km in Abu Dhabi and Dubai. This agreement allows Hyperloop TT to start construction of a hyperloop system. Initial testing of the system will take place in Toulouse, France.

- **April 2018**[^58,^59]
  - Hyperloop Transportation Technologies reveals full-scale passenger capsule.
  - The first passenger capsule was unveiled in Spain and is constructed out of HyperloopTT vibranium a dual layer composite material and was manufactured at the Southern Spain aerospace facilities. The capsule will be tested in Toulouse, France.
  - The capsule had a length of 32 m with an inner cabin length of 15 m, a weight of 5,000 kg.
  - Hyperloop Transportation Technologies signed an agreement for a commercial system in Ukraine (2018)

- **July 2018**[^60]
  - Hyperloop TT to build China’s first hyperloop system starting with an initial 10 km commercial agreement at Tongren in Guizhou Province.

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## Hyperloop Transportation Technologies (HTT)

### Press Articles

<table>
<thead>
<tr>
<th>Date</th>
<th>Events</th>
</tr>
</thead>
</table>
| September 2018<sup>61</sup> | - Hyperloop Transportation Technologies, Partners and Government Stakeholders move forward with regulatory framework.  
- TUV SUD produced the first set of Hyperloop core safety requirements and certification guidelines.  
- Hyperloop TT and Munich Re presented the first insurance framework and licensing as part of future commercial systems.  
- Ukraine, China, Germany, France, United States discuss implementation and adoption. |
| May 2019<sup>62</sup> | - HTT presents certification guidelines to the European Union as a foundation for the hyperloop industry. |
| June 2019<sup>63</sup> | - The Q2 update mentions hyperloop systems are being assembled at the test center in Toulouse, France and that the centre in the process of preparing for human capsule trials in 2020. This testing comes prior to the proposed construction of the commercial system planned for Abu Dhabi. |

### Partnerships

Hyperloop TT is partnered with over 50+ universities, government agencies and private firms. Strategic Partners include:

**Research:** Lawrence Livermore National Laboratory, CEA Tech  
**Design:** PriestmanGoode, MAD Architects, Mormedi  
**Engineering:** Dar Al-Handasah, SBP, Leybold  
**Manufacturing:** Airtificial, Haizea Group, Pacadar  
**Services:** Paul Hastings, Munich Re, TUV SUD, Barkawi  
**Digital:** Nvidia, Re’flekt, Sony Pictures

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<table>
<thead>
<tr>
<th>Company Location</th>
<th>The headquarters of Zeleros are located in Valencia, Spain (founded in 2016)</th>
</tr>
</thead>
</table>
| Published Information     | • Zeleros was founded by students from the Universidad Politencia de Valencia (UPV) following the SpaceX design competition in Texas, USA. The team won top design concept, as well as top propulsion/compression subsystem for technical excellence.  
                            • In 2017, Zeleros partnered with the University of Purdue to build a 12 m tube and prototype pod to carry out testing. Zeleros went on to win a Hyperloop competition for their pod as one of the top 10 global designs and were awarded 60,000 Euros from the Everis Foundation funded by a Spanish Consulting Company.  
                            • In 2018, Zeleros received support from venture capital companies and public funding programs. In 2018, Zeleros announced plans to build a test track in Valencia to be completed by 2020.  
                            • Zeleros have indicated funding in excess of 1.5m euros to further research and design. |
| Geographic Locations      | Zeleros is present in Europe and is in a consortium with European and Canadian Hyperloop Companies, to explore uniform design standards and a shared network. |
| Press Articles            | June 28, 2018  
                            • Canadian and European Hyperloop Leaders Launch Industry-first Partnership to Establish International Standards and Regulatory Framework  
                            • The partnership includes TransPod, Hardt, Zeleros and Hyper Poland  
                            • Zeleros and Siemens form a partnership to develop hyperloop technology |

64 [https://www.politesi.polimi.it/bitstream/10589/151079/1/Hyperloop%20An%20analysis%20of%20its%20fit%20in%20the%20European%20Union_Marta%20de%20Castro%20Perez.pdf](https://www.politesi.polimi.it/bitstream/10589/151079/1/Hyperloop%20An%20analysis%20of%20its%20fit%20in%20the%20European%20Union_Marta%20de%20Castro%20Perez.pdf)  
65 [https://www.politesi.polimi.it/bitstream/10589/151079/1/Hyperloop%20An%20analysis%20of%20its%20fit%20in%20the%20European%20Union_Marta%20de%20Castro%20Perez.pdf](https://www.politesi.polimi.it/bitstream/10589/151079/1/Hyperloop%20An%20analysis%20of%20its%20fit%20in%20the%20European%20Union_Marta%20de%20Castro%20Perez.pdf)  
66 [https://www.politesi.polimi.it/bitstream/10589/151079/1/Hyperloop%20An%20analysis%20of%20its%20fit%20in%20the%20European%20Union_Marta%20de%20Castro%20Perez.pdf](https://www.politesi.polimi.it/bitstream/10589/151079/1/Hyperloop%20An%20analysis%20of%20its%20fit%20in%20the%20European%20Union_Marta%20de%20Castro%20Perez.pdf)  
### Press Articles

February 2020\(^7^0\)

- A consortium of hyperloop companies within Europe and Canada are working to standardise methodology and framework to regulate the Hyperloop travel systems and ensure safety standards. These companies include Hardt, Hyper Poland, TransPod and Zeleros.

### Partnerships

Zeleros has partnered with key industry leaders including \(^7^1,7^2\):

- Altran, Generalitat Valencia, renfe, Climate-KIC, ANGELS, RENFE, Trenlab, PlugandPlay, University of Valencia, Ciemat, ITE, Jesiva, tecnalia, Ceit, Siemens Mobility and more.

Zeleros works with existing industries including:

- MAFEX Spanish Railway Association, Railway Innovation Hub, Spanish Aerospacial and more.

### Hardt

#### Company Location

The headquarters of Hardt are located in Delft, The Netherlands.

#### Published Information

Hardt produces the following studies\(^7^3\):

- Feasibility Studies
- Engineering Studies

**Amsterdam – Frankfurt Kickoff Study (2018)**\(^7^4\)

- The Amsterdam – Frankfurt route is approximately 450 km and is expected to take approximately 50 minutes with 7 intermediate stations situated along the route. The route is expected to serve over 4.3 M residents and carry 48 M passengers annually leading to savings of 83,690 tonnes of

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\(^7^1\) [https://zeleros.com/zeleros/#partners](https://zeleros.com/zeleros/#partners)

\(^7^2\) [https://ec.europa.eu/eipp/desktop/it/projects/project-print-11397.html](https://ec.europa.eu/eipp/desktop/it/projects/project-print-11397.html)

\(^7^3\) [https://hardt.global/research/](https://hardt.global/research/)

## Hardt

### Published Information

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>• This paper written by Hardt co-founders Mars Gueze, Marinus Van Der Meija and others outlines the embarking and disembarking process for future hyperloop passengers. Experiments comparing door widths and number of doors with simulated passengers carrying luggage tested process of highspeed (dis)embarking. The study concluded that narrowing the door width does not influence embarking time and slows disembarking time, half customers also rate the experience negatively. Further, more doors provide a better experience in terms of efficiency however increases manufacturing complexity and chance of failure.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Geographic Locations

| Hardt has developed a strong connection with the Dutch authorities and is exploring options for routes within the country. |
| Europe |
| • Amsterdam – Frankfurt (450 km) |

### Press Articles

<table>
<thead>
<tr>
<th>December 2017</th>
<th>Dutch House of Representatives call for financing of Hyperloop Test Facility (unanimous vote)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The test facility will span approximately 5 km and would cost approximately $120M Euros.</td>
<td></td>
</tr>
<tr>
<td>• Previous testing by Hardt in partnership with BAM has taken place at Delft University in a 30 m long facility.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>June 2018</th>
<th>Canadian and European Hyperloop Leaders Launch Partnership to Establish International Standards and Regulatory Framework</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The partnership includes TransPod, Hardt, Zeleros and HyperPoland</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>September 2018</th>
<th></th>
<th><a href="https://hardt.global/sub/press/research-amsterdam-frankfurt-hyperloop-route-proves-feasibility-hyperloop-europe/">link</a></th>
</tr>
</thead>
</table>

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75 [link](https://link.springer.com/chapter/10.1007/978-3-319-96074-6_23)
76 [link](https://www.google.ca/maps)
77 [link](https://hardt.global/sub/press/dutch-house-representatives-wants-financing-hyperloop-test-facility/)
79 [link](https://hardt.global/sub/press/research-amsterdam-frankfurt-hyperloop-route-proves-feasibility-hyperloop-europe/)
### Press Articles

- Research into Amsterdam-Frankfurt Hyperloop route proves the feasibility of the hyperloop in Europe.
- The proposed route is 450 km long with 7 intermediate stations and is expected to take approximately 50 minutes in contrast with 4 hours using regular transit.
- This route would carry 48M passengers and would save 83,690 tonnes of CO2 emissions per year from airline traffic.

**June 2019**

- Hardt hyperloop is a step closer to offering green alternatives to short-haul flights
- The lane-switching technology developed by Hardt allows hyperloop vehicles to switch from one lane to another without additional or moving components.

**December 2019**

- A hyperloop test facility is planned for Groningen, Netherlands with construction planned for 2020 and completion planned for 2022. The facility will host a 3 km test track as well as a public learning centre.

### Partnerships

**Global Partnerships**

**Tata Steel**

- One of Europe’s leading steel producers and manufacturers.

**InnoEnergy**

- Innovation engine for sustainable energy across Europe, specialties in education, innovation projects and business creation services.

**Royal Bam**

- Construction group active in real estate and civil engineering businesses.

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<table>
<thead>
<tr>
<th>Partnerships</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardt</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Royal IHC</strong></td>
<td>Supplier of efficient equipment, vessels and services for offshore dredging and wet mining markets. This company has in-depth knowledge of the engineering and manufacturing industries.</td>
</tr>
<tr>
<td><strong>Deutsche Bahn</strong></td>
<td>Engineering and consulting firm located within Germany.</td>
</tr>
<tr>
<td><strong>NS</strong></td>
<td>Principal passenger railway operator of the Netherlands.</td>
</tr>
<tr>
<td><strong>UNStudio</strong></td>
<td>International architectural firm with offices in Amsterdam, Hong Kong and Shanghai.</td>
</tr>
<tr>
<td><strong>Contitech</strong></td>
<td>Rail company dedicated to providing comfort, safety, and fire protection in high speed rail.</td>
</tr>
<tr>
<td><strong>Goudsmit Magnetics</strong></td>
<td>International producer of magnetic systems for various applications with production facilities in China and Czech Republic.</td>
</tr>
<tr>
<td><strong>ENGIE Laborelec</strong></td>
<td>Electrical power technology company located in Belgium, the Netherlands, Germany, Chile and Abu Dhabi.</td>
</tr>
<tr>
<td><strong>Busch</strong></td>
<td>Leading manufacturer of vacuum generators for a variety of applications.</td>
</tr>
<tr>
<td><strong>Prysmian Group</strong></td>
<td>Located in Delft, Netherlands, this company focuses on energy and telecom cable systems industries.</td>
</tr>
<tr>
<td><strong>Schiphol Group</strong></td>
<td>Amsterdam Schiphol Airport is part of the Schipol Group an operator of airports in the Netherlands and abroad.</td>
</tr>
<tr>
<td><strong>Koolen Industries</strong></td>
<td>Koolen industries specialises in clean energy (wind and solar).</td>
</tr>
</tbody>
</table>
### Partnership

<table>
<thead>
<tr>
<th>Company Location</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU Delft</td>
<td>Delft university of technology is located in the Netherlands and specialized in science and technology.</td>
</tr>
<tr>
<td>Allplan Engineering</td>
<td>Engineering consulting firm specializing in infrastructure construction.</td>
</tr>
<tr>
<td>SCIA Engineer</td>
<td>Software company for material structural analysis suitable for a variety of structures.</td>
</tr>
<tr>
<td>Accenture Interactive</td>
<td>Marketing firm specializing in technology companies.</td>
</tr>
</tbody>
</table>

### Hyper Poland

<table>
<thead>
<tr>
<th>Company Location</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyper Poland was founded in 2017 and is located in Poland.</td>
<td></td>
</tr>
</tbody>
</table>

#### Information Published

Hyper Poland has developed technology for a three-step system for easier integration of hyperloop, the MagRail system uses passive magnetic levitation train while operating on existing tracks. Using this technology, the hybrid solution can reach speeds up to 415 km/hour. This technology can further be transformed into a vacuum system, HyperRail, which can reach a top speed of 600 km/hour. Hyper Poland’s hyperloop technology would require a new rail track system and can reach up to 1,200 km/hour and would be the final stage of the three-step implementation system[^3].

#### Geographic Locations

Hyper Poland continue to develop their technology and have very little publicly available information on routes.

- **Poland[^4]**
  - Kraków - Gdansk (~600 km)

[^4]: [https://www.google.ca/maps](https://www.google.ca/maps)
<table>
<thead>
<tr>
<th>Press Articles</th>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 2016</td>
<td>Hyper Poland was announced as a finalist at the Dubai Future Foundation International Hyperloop Competition. The competition involved designing a prototype for a hyperloop train that would reduce the travel time between Dubai and Fujairah to 20 minutes.</td>
<td></td>
</tr>
<tr>
<td>June 2018</td>
<td>Canadian and European hyperloop leaders launch industry-first partnership to establish international standards and regulatory framework. The partnership includes TransPod, Hardt, Zeleros and HyperPoland.</td>
<td></td>
</tr>
<tr>
<td>May 2019</td>
<td>Hyper Poland receives $5.6 M (CAD) in funding to produce a high-speed 500 m long test track for trains travelling up to 300 km/hr. This track will help test linear drive and magnetic levitation with the vehicles.</td>
<td></td>
</tr>
<tr>
<td>July 2019</td>
<td>Hyper Poland is recognized as a top start-up in the mobility sector for developing a three-step system for implementing the hyperloop technologies in Poland.</td>
<td></td>
</tr>
<tr>
<td>November 2019</td>
<td>Hyper Poland reveals its MagRail transportation technology and showed a live demonstration of a high-speed rail model system in Warsaw, Poland. The 48 m track was made at a 1:5 scale and the maximum speed reached 50 km/hr. The MagRail system can be fully integrated with existing rail structures and can reach up to 300 km/hour. Hyper Poland also states that the cost to implement this system would be 25% lower compared to high-speed rail.</td>
<td></td>
</tr>
</tbody>
</table>

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89 [https://ecotechdaily.net/hyper-poland-reveals-their-magrail-transport-technology/](https://ecotechdaily.net/hyper-poland-reveals-their-magrail-transport-technology/)
## Hyper Poland

| Partnerships | Hyper Poland has the following partners from R&D and IT areas:
<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>• Tme.eu</td>
</tr>
<tr>
<td></td>
<td>• Polish Airlines</td>
</tr>
<tr>
<td></td>
<td>• Instytut Elektrotechniki</td>
</tr>
<tr>
<td></td>
<td>• Tukasievicz Insytut Lotnictwa</td>
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<tr>
<td></td>
<td>• Instytut Kolejnictwa</td>
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<td></td>
<td>• JMT</td>
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<td></td>
<td>• Igus</td>
</tr>
</tbody>
</table>

## Swisspod

<table>
<thead>
<tr>
<th>Location</th>
<th>Switzerland and was founded in 2019 by winners of SpaceX competition (Dennis Tudor and Mario Paolone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Published</td>
<td>Optimal Design of the Propulsion System of an Hyperloop Capsule (2019)</td>
</tr>
</tbody>
</table>

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91 [https://swisspod.ch/](https://swisspod.ch/)
| Information | • This article was prepared by Swisspod founder and CEO Dennis Tudor and Mario Paolone to assess the optimal design of the propulsion system within a hyperloop capsule that is supplied by batteries and further to propose a sizing method for the transportation system that would meet the system’s power requirements.  
• The findings of the article state that an energy capacity of 0.5 MWh and power rating below 6.25 MW would enable an energy consumption of 10-50 Wh/km/pasenger.  
• This article was prepared by Swisspod founder and CEO Dennis Tudor and Mario Paolone to assess the influence of equivalent circuit battery models on the optimal design of a hyperloop system. |
|---|---|
| Geographic Locations | Switzerland  
• Zurich – Geneva (250 km) |
| Press Articles | July 2019  
• The goal of Swisspod is make hyperloop a reality in Switzerland with the first corridor proposed between Zurich and Geneva in 17 minutes for both passengers and cargo.  
November 2019  
• Co-Founder and CEO Denis Tudor gives a TEDX talk on the importance of efficiency in speed in terms of Climate Change. The talk outlines how Swisspod can help with the reduction of CO2 emissions on the Zurich-Geneva corridor. |
| Partnerships | The partners of Swisspod include multiple consulting, technology and academic associations:  
• EPFL  
• School of Canton Du Vaud  
• Nomads Foundation |

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94 [https://swisspod.ch/](https://swisspod.ch/)  
95 [https://swisspod.ch/partners/](https://swisspod.ch/partners/)
| Company | Collombey Muraz  
|         | Swissmetro  
|         | DigitalYA  
|         | University of St. Gallen  
| Location | The KRRI is run by the Korean government and is located within South Korea.  
| Information Published | Numerical Analysis of Aerodynamic Characteristics of Hyperloop System (2018)  
|                     | This article outlines the analysis of systems of aerodynamic drag in terms of the hyperloop. Factors that could affect aerodynamic drag include the blockage ratio (BR), pod speed/length, tube pressure, and temperature. Two-dimensional asymmetric simulations were performed to monitor changes in the above parameters under set conditions. Findings concluded that as the BR increased, the pressure drag was affected due to the critical Mach number. Further, as the pod length increased, total drag and pressure drag were not affected. This is due to flow choking that occurs around the pod. High tube temperatures also increase the speed of sound and reduce the Mach number which in turn delay choking and therefore reduce the aerodynamic drag. These results are applicable to fundamental hyperloop design.  
| Geographic Locations | South Korea  
|                     | Seoul – Pusan (~325 km)  
|                     | Busan – Pyongyang (~530 km)  
|                     | Seoul – Busan (~500 km)  
| Press Articles | February 2017  
|                 | Eight South Korean organizations formed a multi-year strategic partnership and took part in a memorandum to develop an understanding of the [file:///C:/Users/mikayla.reid/Downloads/energies-12-00518.pdf](file:///C:/Users/mikayla.reid/Downloads/energies-12-00518.pdf)  
|                 | [https://sudonull.com/post/20991-South-Korea-is-developing-its-Hyperloop](https://sudonull.com/post/20991-South-Korea-is-developing-its-Hyperloop)  
### Press Articles

hyperloop system, the HyperTube Express (HTX). The partnership included the Ulsan National Institute of Science and Technology (UNIST), Electronics and Telecommunications Research Institute (ETRI), Hyper-connected Research Laboratory, Korea Institute of Civil Engineering and Building Technology, the Korean Railroad Institute (KRRI), the Institute of Machinery & Materials and Korea Transport Institute.

- The HTX system is powered by magnetics and has a proposed speed of 1000 km/hour meaning that a trip from Seoul to Busan would take approximately 20 minutes. The pod would be 21 m in length and would carry up to 20 passengers at a time, the train would also contain an air compressor at the front to reduce friction and resistance.
- KRRI has plans to test the electromagnetic and core technologies as well as developing infrastructure for the project. KRRI has invested $21 M USD into the nine-year project.

May 2018

- KRRI unveils prototype of a vacuum tube to be used in hyperloop project. KRRI states that the tube maintains less than 1/1000 atmospheres to minimize air resistance. The tube is composed of pressurized steel and is 10 m in length, 2640 mm in diameter and 23 mm in thickness.

### Partnerships

KRRI has formed the following multi-year partnerships:

- Ulsan National Institute of Science and Technology (UNIST)
- Electronics and Telecommunications Research Institute (ETRI)
- Hyper-connected Research Laboratory
- Korea Institute of Civil Engineering and Building Technology
- Korean Railroad Institute (KRRI)
- Institute of Machinery & Materials and Korea Transport Institute

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APPENDIX

PYTHON MODELLING PROCESS OVERVIEW
Appendix F

Appendix F – Python Modelling Methodology Process Overview

AECOM’s subconsultant Continuum Industries Ltd made use of its proprietary parametric models to simulate the performance of different Hyperloop systems and estimate their costs. The models, which were developed in Python version 3.7, can be broadly split into four below listed categories. See Figure F1 below shows a typical modelling workflow.

1. Technology models (e.g. propulsion, levitation, power delivery)
2. Trajectory model (e.g. vehicle movement)
3. System models (e.g. combined technology and trajectory models that form a system for a given route)
4. System of-systems model (e.g. range of different possible system models)

The key outputs from the models include: 1) Power consumption, power loss; and 2) Capital cost

Figure F1: Model Workflow Flowchart
Technology Models

These models capture Hyperloop-specific technologies such as propulsion, levitation, energy storage, and power delivery, which are modelled through analytical equations. In simple terms, generative design procedures are used by the models to create suitable technology components for a given set of desired performance parameters (e.g. maximum speed/acceleration, mass to be accelerated/levitated, air gap). A bill of materials is generated by the models for costing purposes, as well as projected assembly time. The design procedure is then reiterated several times, taking into account the added mass of the newly designed component to ensure a feasible solution. Finally, a simulation is performed, returning the worst-case and steady-state power consumption/loss of the component.

The technology models are independent of route length and work on a per-vehicle basis. For example, a propulsion system model will generate a design of a linear electric motor just long enough to provide the required thrust for a vehicle with a given mass, travelling at a certain speed and a set air gap – this results in a “unit propulsion block”, which is generally around 3 m long. These unit blocks are then stitched together in a system-level model. The length of levitation unit blocks is also tied to the propulsion unit blocks, whereas energy storage and power delivery are counted per-vehicle, with no particular length.

It should be noted that the technology models are highly generalized to represent broader technology types. As such, the designs produced by these models are by no means optimal and follow simplified geometries. The electromagnetic simulations are performed by approximate-form analytical equations (such as those of an equivalent circuit model), which have a known tendency to overestimate real-world performance. The modelling results are used only to provide a high-level, relative comparison between different technology configurations.
The following technology models were used:

- **Propulsion**
  - Linear induction motor with a conductive sheet secondary (LIM-CS)
  - Linear induction motor with a conductive ladder secondary (LIM-CL)
  - Linear synchronous motor with a permanent magnet secondary (LSM-PM)
  - Axial compressor (simplified model)

- **Levitation**
  - Active levitation through a combination of electromagnets and permanent magnets
  - Passive levitation through permanent magnets and a conductive sheet track
  - Passive levitation through permanent magnets and a conductive ladder track

- **Power delivery**
  - Inverter
  - Energy storage (lithium-ion battery cell assembly)
  - Conductors
  - Power substations
  - Contactless power transfer (simplified model)

**Trajectory Model**

This model defines the movement of a vehicle within the tube using sets of equations of motion. It has two primary purposes:

1. To feed desired performance parameters into the technology models. In this case, the output of the trajectory model is a set of four curves:
   - Speed versus distance/time
   - Acceleration versus distance
   - Acceleration versus time

2. To perform isolated calculations using the equations of motion, such as finding the braking distance of a vehicle.

**System Models**

These models create a specific Hyperloop system by instantiating system-wide parameters such as route length, combining various technology models and giving them inputs from the trajectory model. The type of technology used in a system is configured manually, the model then lays out the unit blocks generated by the technology models across the given length of the route and adjusts their desired performance parameters based on outputs from the trajectory model.
Different technologies may be used on different parts of the route (see Section 3.2.4), resulting in many possible system configurations.

**System-of-Systems Model**

This is the top-level model, where all the previous models are interconnected, and their results evaluated. In essence, this model represents several configurations of the system model and evaluates them for energy efficiency and cost. The example system configurations in Section 3.2.7 were evaluated using this modelling methodology.

The following systems were evaluated:

- **Vehicle-side propulsion**
  - Propulsion types: LIM-CS, LIM-CS + compressor, LIM-CL, LIM-CL + compressor
  - Levitation: active, passive (sheet), passive (ladder)
  - Primary power delivery though: on-board energy storage, contactless power transfer

- **Infrastructure-side propulsion**
  - Propulsion types: LSM-PM, LSM-PM + compressor
  - Levitation: active, passive (sheet), passive (ladder)
  - Primary power delivery though: cable connection to a power substation

- **Intermittent propulsion**:
  - Propulsion types: LSM-PM + compressor, LSM-PM + LIM-CS + compressor, LSM-PM + LIM-CL + compressor
  - Levitation: active, passive (sheet), passive (ladder)
  - Primary power delivery though: cable connection to a power substation + on-board energy storage, cable connection to a power substation + contactless power transfer.
APPENDIX

NASA TRL DEFINITIONS
## Appendix G

### Appendix G – NASA’s Technology Readiness Level Definitions

<table>
<thead>
<tr>
<th>TRL</th>
<th>Definition</th>
<th>Hardware Description</th>
<th>Software Description</th>
<th>Exit Criteria</th>
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<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported.</td>
<td>Scientific knowledge generated underpinning hardware technology concepts/applications.</td>
<td>Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.</td>
<td>Peer reviewed publication of research underlying the proposed concept/application.</td>
</tr>
<tr>
<td>2</td>
<td>Technology concept and/or application formulated.</td>
<td>Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.</td>
<td>Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.</td>
<td>Documented description of the application/concept that addresses feasibility and benefit.</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental critical function and/or characteristic proof of concept.</td>
<td>Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical predictions.</td>
<td>Development of limited functionality to validate critical properties and predictions using non-integrated software components.</td>
<td>Documented analytical/experimental results validating predictions of key parameters.</td>
</tr>
<tr>
<td>4</td>
<td>Component and/or breadboard validation in laboratory environment.</td>
<td>A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.</td>
<td>Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.</td>
<td>Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.</td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in relevant environment.</td>
<td>A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.</td>
<td>End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.</td>
<td>Documented test performance demonstrating agreement with analytical predictions. Documented definitions of scaling requirements.</td>
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<td>System/sub-system model or prototype demonstration in an operational environment.</td>
<td>A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.</td>
<td>Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.</td>
<td>Documented test performance demonstrating agreement with analytical predictions.</td>
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<td>System prototype demonstration in an operational environment.</td>
<td>A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).</td>
<td>Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational feasibility. Most software bugs removed. Limited documentation available.</td>
<td>Documented test performance demonstrating agreement with analytical predictions.</td>
</tr>
<tr>
<td></td>
<td>Actual system completed and &quot;flight qualified&quot; through test and demonstration.</td>
<td>The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).</td>
<td>All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation completed.</td>
<td>Documented test performance verifying analytical predictions.</td>
</tr>
<tr>
<td></td>
<td>Actual system flight proven through successful mission operations.</td>
<td>The final product is successfully operated in an actual mission.</td>
<td>All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.</td>
<td>Documented mission operational results.</td>
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Appendix H

Appendix H – Economic Questionnaire to Hyperloop Companies

AECOM has developed a bottom-up costing model for a 500 km Hyperloop system with two tubes and two stations in Canada – and would like to verify some of the assumptions made for specific system components. As before, your answers to each question will not be reported individually or attributed directly to you.

Q1. Vacuum Pumps & Power Stations
   o Please can you provide an estimate of the capital costs of installation of vacuum pumps for this illustrative 500 km, double tube hyperloop system and, if possible, indicate the approximate number used.
   o Please can you provide an estimate of the capital costs of installation of power stations for this illustrative 500 km, double tube hyperloop system and, if possible, indicate the approximate number used.

Q2. Emergency Exits
   o Please can you provide an estimate of the capital costs of installing emergency exits for this illustrative 500 km, double tube hyperloop system (additional to the costs of your typical tube and guideway infrastructure) and, if possible, indicate the number used / spacing of each emergency exit.

Q3. Station Systems / Switches (e.g. Airlocks, Low / High-Speed Switches)
   o Please can you provide an estimate of the capital costs associated with the station-specific systems at each Hyperloop station for this illustrative 500km, double tube hyperloop system and confirm what this cost includes?
   o Please can you provide an estimate of the capital costs associated with a single high-speed switch for this illustrative 500 km, double tube hyperloop system (additional to the costs of your typical guideway infrastructure) or indicate the distance over which a high-speed switch is performed and the expected increase in capital cost relative to your guideway infrastructure.

Q4. Capsules / Pods
   o Please can you provide an estimate of the capital costs of the pods that would be in operation for this illustrative 500 km, double tube hyperloop system and, if possible, indicate the number of pods that this includes.
Q5. Operational Expenditure

- Please can you provide an estimate of the energy consumption for the typical operation of one capsule for this illustrative 500 km, double tube hyperloop system and, if possible, indicate the passenger capacity of the capsule.

- Please can you provide an estimate of the energy consumption for tube operations, separate from any propulsion or levitation energy consumption, for this illustrative 500 km, double tube hyperloop system?

- Please can you provide an estimate of the personnel required for this illustrative 500 km, double tube hyperloop system for:
  - Operating capsule movements.
  - Supervising/assisting passenger movement in stations.
  - Ticketing.
  - Capsule maintenance / inspection.
  - Tube maintenance/inspection.
  - Emergency personnel to respond to immobilised capsules or tube incidents.
  - Management, marketing and administration overhead.

NB: If you’re not able to provide confident estimates for some questions then AECOM is happy to accept ranges or for you to indicate any additional assumptions that you think are important to take into account (e.g. the low range = base estimate and the high range = base cost plus contingency). AECOM is most interested in verifying the likely unit or overall costs of specific components rather than precise quantities or spacing of each specific component.