

A Reality Check on Maglev Technology for the Hyperloop Transportation System

Status Update After a Decade of Development

By Jonas Kristiansen Nøland and Jonathan Bird

Abstract

Ten years ago, the concept of the hyperloop vacuum train promised to revolutionize transportation by offering a fast, inexpensive, and eco-friendly alternative to traditional modes of travel. The key components of the hyperloop are a vacuum tube, magnetic levitation, and linear electric propulsion technology, which is envisaged to achieve surface velocities approaching the speed of sound. This paper presents the functionalities of an ideal hyperloop transportation system (HTS) with a low-cost track and a lightweight hyperloop capsule. We show how this ideal system is indeed difficult to achieve in reality. Despite the potential benefits, hyperloop technology still lacks experimental evidence at subsonic speeds to reach a higher level of technological readiness. Taking one step back, hyperloop has lessons to learn from the maglev research and experiments in the 1970s. In fact, there are many unresolved challenges associated with maglev technologies, even at moderate speeds, which need to be recognized before reaching the whole way into the subsonic speed domain. This paper will provide a status update after ten years of hyperloop research and development.

Introduction

Vacuum transportation has a fascinating, long-forgotten history dating back over two centuries to when George Medhurst, an English inventor, proposed moving through tunnels of thin air [1]. Despite Medhurst's visionary ideas, some of them were met with ridicule, as expressed through satirical art [2]. It wasn't until a century later that Robert Goddard proposed airless tunnels assisted by magnetic levitation (maglev) [3]. At that time, the bullet train was already viewed as an engineering blunder by Imperial College Professor Rod Smith [4]. Even though many nowadays consider the modern rail as outdated, it is, in reality, difficult to beat the high-speed rail's low rolling resistance [5]. The competing maglev solutions need to expend significant power to provide the levitation. In fact, it is quite challenging to invent a more efficient mass transportation system that can address future sustainability goals and also be cost-justifiable.

A decade ago, there was a great deal of excitement surrounding hyperloop technology as a promising solution for passenger and cargo transportation. Hyperloop has since then received criticism for being a rebranding of a 200-year-old idea [6]. Despite numerous feasibility studies published since then, the

development of hyperloop technology is still in its infancy. What has been accomplished is a mere fraction of what was initially intended. A couple of years ago, the European Commission launched calls for hyperloop projects with the goal of achieving technology readiness level 6 (TRL6) in Europe by the end of the decade. This goal contradicts the fact that many hyperloop developers had initially promised a fully functional commercial system by now. In reality, climbing the technology-readiness chain has proven to be more challenging than anticipated (see TRL classification info box below).

The transportation sector's emissions in the EU have increased by 33 % since 1990, while other industries, such as agriculture and manufacturing, have reduced emissions by 32% [7]. This trend underscores the importance of adopting sustainable mobility solutions to address the environmental crisis. To reduce travel-related emissions by 90 % by 2050 [8], [9], the EU has identified hyperloop as a key strategic solution [10]. As the hyperloop is envisioned to be fully electric, it is considered a clean mobility technology [11]. Despite its potential, the hyperloop's intensive infrastructure requirements pose a significant challenge. Nevertheless, Europe has a robust hyperloop presence in both industry and academia and is poised to take a global leadership role [12]–[14], while there are also a lot of important work going on in the US and in Canada as well. Nonetheless, the most competitive maglev competence exists in countries like Japan and China. Therefore, it would be of great benefit to transfer more of this knowledge to hyperloop developments.

The present article provides the following information.

- ✓ First, the different hyperloop developers and their recent activities will be briefly described;
- ✓ Second, the key objectives of an ideal scalable hyperloop system will be discussed;
- ✓ Then, the opportunities and the importance of delivering a sub-scale laboratory demonstrator for maturing hyperloop's core technologies are presented; and,
- ✓ Finally, the article is concluded with a future technology outlook.

TRL classification: The TRL system is an international classification that determines the stage of development of a technology, with level 1 representing basic technological principles and level 9 indicating that the system has been tested in an operational and functional environment. At level 6, one or more hyperloop prototypes are expected to be validated in a relevant environment.

Status Update from Hyperloop Developers

The Hyperloop concept has been developed by eight major companies worldwide. These are mostly located in Europe and North America, as highlighted in Table 1. Their target subsonic speeds range between 700 kilometers per hour (km/h) or above 1200 km/h, approaching the speed of sound, and they usually consider route distances up to 1500 km. The number of passengers per capsule is also an open question, as larger vehicles will generate more throughput, while smaller vehicles will be easier to design but will have to compensate with shorter headways between each capsule.

Since Elon Musk proposed a hyperloop route from Los Angeles to San Francisco in 2013, several other hyperloop demonstration projects have been suggested. Among them include HyperloopOne's route from

Chicago to Columbus to Pittsburg, TransPod's Calgary to Edmonton, and HyperloopTT's Dubai to Abu Dhabi.

Some companies have recently shifted their focus from passenger transport, with cargo as a supplement, to solely freight logistics. For instance, Hyperloop One, an early entry in the field, downscaled in 2022 its ambitions for passenger transportation and dismissed half of its employees [15]. Later, in 2023, it was announced that HyperloopOne is shutting down their activity completely [16]. Even though they were able to build prototypes in the Nevada desert, they still had doubts that they could solve their major engineering challenges.

Table 1 – Major hyperloop developers worldwide and their general performance targets.

Company	Country	Cruising speed	Passengers per capsule	Established – Closed
Zeleros	Spain	1000 km/h	50 – 200	2016 –
Hardt	Netherlands	700 km/h	40 – 80	2016 –
Swisspod	Switzerland/United States	1200 km/h	n/a	2019 –
Nevomo	Poland	n/a	n/a	2017 –
TransPod	Canada/France	1000 km/h	≤ 54	2015 –
Hyperloop One	United States	1223 km/h	Cargo only	2014 – 2023
HyperloopTT	United States/France	1223 km/h	28 – 48	2013 –
DGWHyperloop	India	1000 km/h	Cargo only	2015 –

Functionalities of an Ideal Hyperloop System

Figure 1 outlines the objectives and key features of a scalable hyperloop concept that uses onboard linear electromagnetic propulsion and electrodynamic suspension. This design eliminates the need for active track components to maintain levitation while the capsule is in motion, although it does require auxiliary support wheels during take-off and landing. By making the capsule energy-autonomous and self-propelled, infrastructure costs along the track can be significantly reduced, as only passive components are needed. This solves the scalability problem of current hyperloop solutions. Moreover, the subsonic electrodynamic levitation of this configuration has a low magnetic drag energy at sufficiently high subsonic speeds [17]. However, even though the magnetic drag tends to be low at higher speeds, it must not be confused with the fact that the levitation system's power consumption still increases at higher speeds.

Nevertheless, the concept of a self-propelled, energy-autonomous hyperloop solution depicted in Figure 1 is challenging to realize. An easier technical solution would be based on the concept of the 'track as a propulsor,' similar to the classical German Transrapid maglev system [18]. However, this approach has

already been deemed a commercial failure due to the exorbitant initial cost of the track infrastructure [19], which was then far too expensive to pay back.

Initially, some hyperloop companies pursued the ‘track as a propulsor’ approach again, which enables a lightweight capsule that can be developed more quickly, but at the expense of scalability (e.g., Hardt Hyperloop’s original design). Recent research also reflects this trend. However, a major struggle with this approach is the inability to continuously utilize the infrastructure-intensive track since the headway between capsules cannot be lower than 30 seconds [20]. With a cruising speed of 1000 km/h, 30 seconds headway implies that there is more than 8 kilometers of unutilized track between each capsule. Thus, the utilization of the infrastructure indeed is very low.

One alternative idea is to propose an aerodynamic propulsion system onboard the capsule to address the scalability problem (as was initially proposed by Zeleros), but this approach is ineffective due to high design pressure and too much air inside the tube. In fact, the optimal pressure levels for the hyperloop being are in the range from 0.11 % to 1.70 % of the atmospheric level [21]. In the case of Zeleros’s aerodynamic propulsion, the drag will be up to a hundred times higher than the ideal range, making it ineffective. Then, the only solution left is a solution based on the idealized hyperloop system in Figure 1.

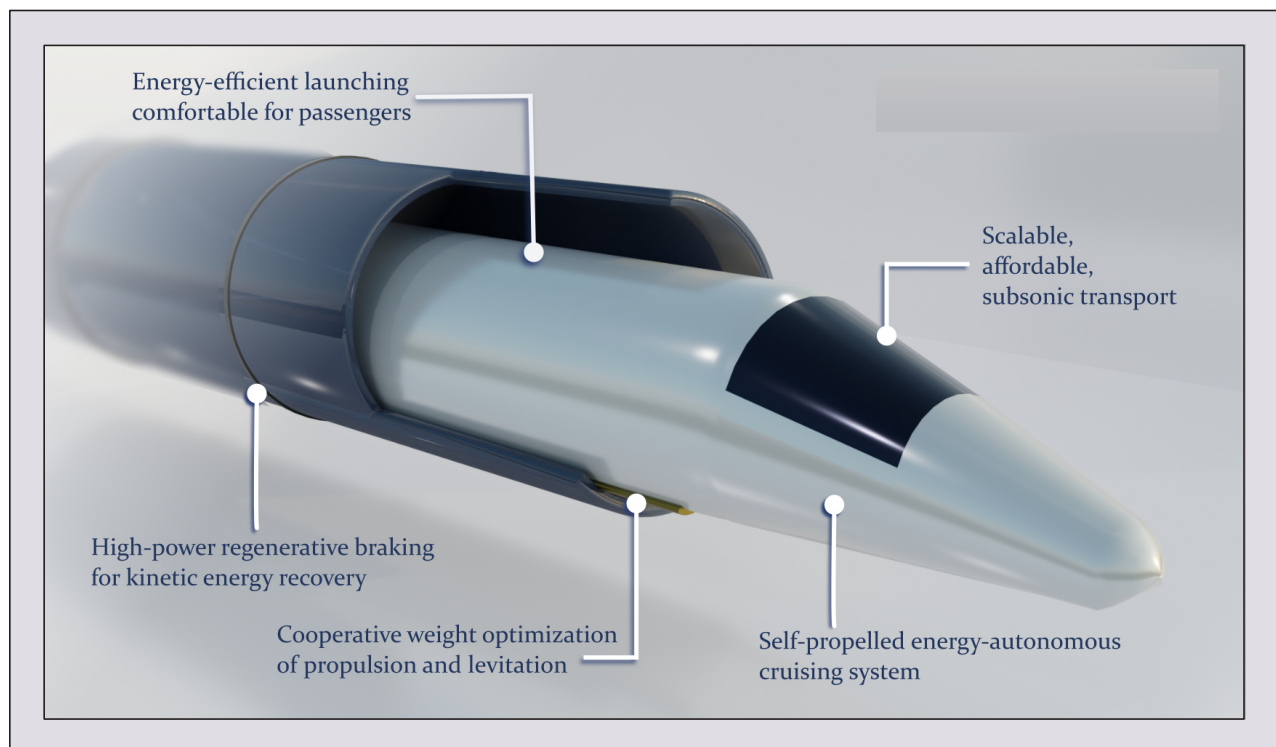


Figure 1 – Highlighting of the key objectives of a passive guideway hyperloop transportation system.

To illustrate the challenges of building a scalable hyperloop concept, two examples of passive track design are shown in Figure 2. These passive guideway design examples use either a linear synchronous reluctance motor (LSRM) or a double-sided linear induction motor (DS-LIM) as the primary propulsion component during cruising. This will minimize the track electrification but require significant onboard battery storage. Nevertheless, one of the concepts (option 2) could achieve energy savings onboard the capsule by utilizing

an integrated electromagnetic launch system that integrates a permanent magnet linear synchronous motor (PM-LSM) installed on the track. This additional track motor could be located near the stations and would leverage the magnetization from the auxiliary hybrid electromagnetic suspension during acceleration. Moreover, the same auxiliary suspension would be responsible for stabilizing the primary electrodynamic suspension during cruising [22]. To establish electromagnetic launch, coils would be distributed along the track to ensure sufficient acceleration force during the launch segment of the track, while energy harvesting using the linear induction motor could be possible during deceleration or acceleration, provided an energy buffering system meets the charging restrictions of the onboard storage.

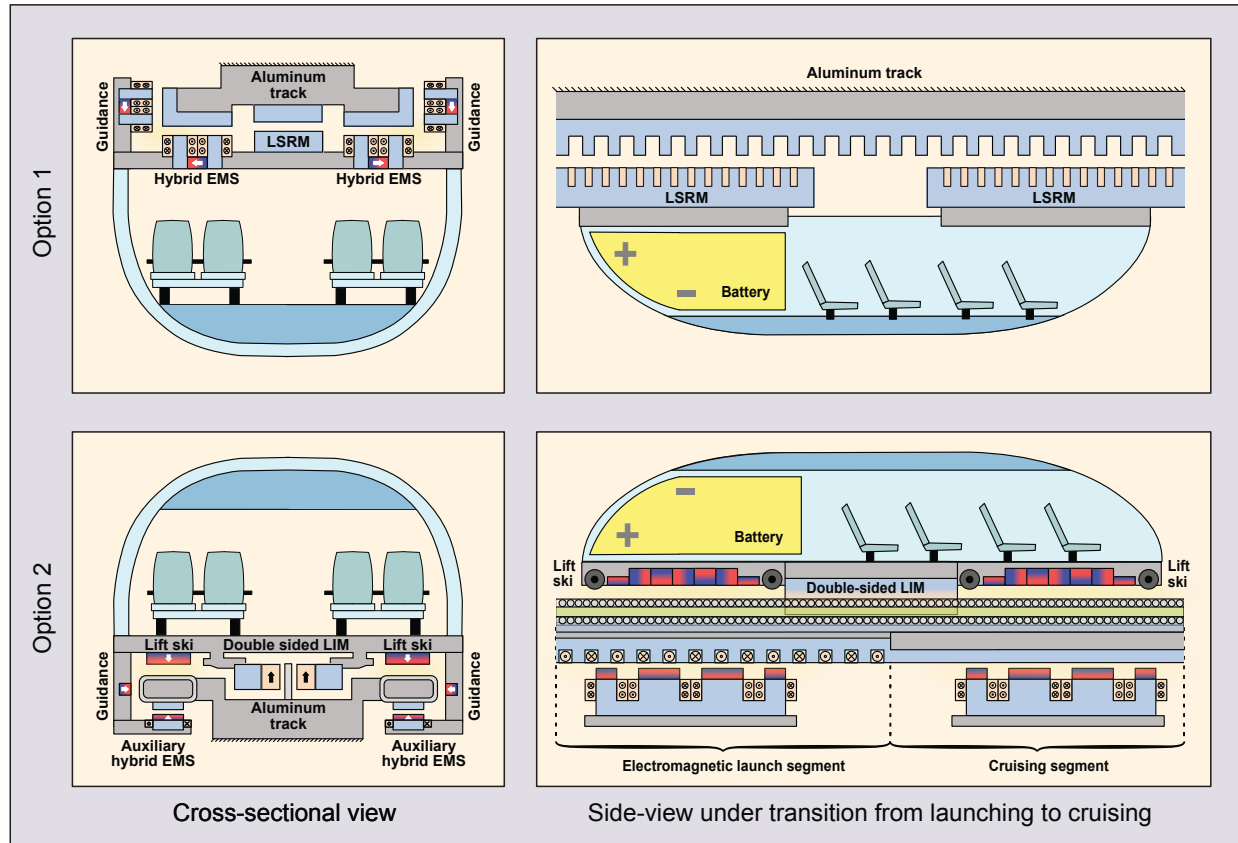


Figure 2 – Two proposed low infrastructure solutions depicted in cross-sectional and side view [18], [22], [23].

The two passive guideway concepts shown in Figure 2 have different capsule arrangements: one with a hanging capsule and one with the capsule floating over the track. Option 1 is the solution proposed by Hardt Hyperloop [23], employing an LSRM. Hardt's concept was pioneered in the 1970s and then revisited by Swissmetro in the 2000s [24], [25]. Important works in this area include Levi (1973) [26], Slemon (1979) [27], and Boldea *et al.* (1988) [28]. A test setup in Canada investigated a 3-pole homopolar linear synchronous motor on a 2-meter diameter rotary wheel test setup. It was found that there are too high eddy current losses at high speeds when solid poles are used [27], which emphasizes the need for laminations, like what is required for the LSRM.

Option 1's main drawbacks are that it requires laminations along the track, requires vertical support, and does not take advantage of ground support. With an electromagnetic suspension system (EMS), the

guideway needs to be elevated into a track roof, which significantly increases infrastructure support costs, as load-bearing weight cannot be directly transferred to the ground.

Option 2 also has significant challenges in terms of cost. If one compares it with the simplicity of high-speed rail, then option 2 needs to wrap around the guideway, making it extremely expensive compared to the high-speed rail. There are also challenges with respect to finding a lane-switching solution for the system. The mechanical support of the vertical plate of the linear induction motor will also be structurally challenging and costly to maintain. Very small angular dimensional tolerance inaccuracies will be catastrophic. Furthermore, the use of a vertical plate makes cornering extremely difficult to achieve when operating with a required long linear motor [29].

Another issue with option 2 is the fact that the LIM topology is typically used for low-to-medium speed propulsion, such as 110 km/h. In fact, there was an immense amount of research that was conducted on the LIMs and double-sided LIMs in the 1970s and early 1980s for high-speed transportation that seems to have been forgotten as they are not much cited [30]–[34].

For example, General Electric conducted high-speed tests of the DS-LIM up to 483 km/h using a 2-meter diameter rotating disc [35]. Such laboratory studies do not seem to be published for the newly developed hyperloop technologies. High-speed maglev vehicle studies were conducted by, for example, Japan Airlines, in which a double-sided LIM was operated up to 300 km/h [30]. Both the US and West-German governments also heavily supported double-sided LIM-based maglev test vehicles [31]. Also, the Transrapid 04 used a double-sided LIM [32].

The past studies showed that the linear induction motor's pole pitch should be increased when operated at higher speeds so as to counteract the end-effect that greatly degrades the thrust at high speeds. The normal forces also start to become an issue for the LIM at high speeds. The LIM would likely need to be many meters long to be feasible to operate in the subsonic speed range around 1000 km/h, which might be impractical. In summary, to operate a double-sided LIM at subsonic speeds several unresolved challenges must be overcome:

- ✓ First, it is mechanically difficult to build aluminum sheets to stay precise vertically and maintain very small airgap over many kilometers, as slight angle deviations cause airgap changes;
- ✓ Second, lane-switching or cornering will be a major issue when considering long double-sided LIMs;
- ✓ Third, the wrap around and elevated guideway designed to very tight tolerances will be extremely cost prohibitive to build; and,
- ✓ Fourth, the successful demonstration of a high-speed LIM design has yet to be demonstrated.

These myriad mechanical and electrical issues were not solved in the 1970s and 1980s at speeds of 400 km/h to 500 km/h, and it will not get easier for higher velocities with even longer double-sided LIMs. Hyperloop developers today need to become familiar with the unresolved issues at lower speeds before pursuing subsonic speeds [31], [32].

Overall, due to the inherent drawbacks of option 2, option 1 seems to be a more competitive solution. However, the costs are still perceived to be excessive, considering that track laminations need to be

installed on the capsule roof or the vehicle must wrap around the track like for the case in option 2. There are very good infrastructure cost reasons that have prevented the widespread use of suspension trains (trains that hang from or wrap around a track structure). Therefore, it will be difficult to justify much higher costs for use in a maglev system that also requires laminations to be installed along the girders.

A path forward would be to first consider the issues from the customer's perspective. Since if trains are not hanging or wrapping around a girder why would transit operators now start using such costly designs when they were not adopted in the 1980s? The design of a passive flat guideway maglev system that can be integrated into existing infrastructure would likely lead to the lowest cost design and therefore be more competitive with existing high-speed trains.

Importance of Innovative Laboratory Demonstrators

The current state of research in the electrical domain of hyperloop is quite limited. Hyperloop propulsion investigations at the relevant subsonic speeds are merely simulation-based and not experimental. For example, Yi *et al.* (2018) studied a multi-megawatt, subsonic hyperloop propulsion system via three-dimensional (3-D) electromagnetic finite element analysis (FEA) [36]. They report a cruising efficiency of 70 %, and the power factor was as low as 30 % when operating at 1000 km/h. However, it is worth noting that this was just a simulation study and that the assumption of an ultra-high track conductivity will cause heating and likely structural problems along the guideway. Similarly, other hyperloop feasibility studies are limited to analytical analysis, system modeling and simulation, and miniaturized-scale experiments at low surface speeds.

To address the hyperloop knowledge gaps, experimental testing techniques should be developed at subsonic speeds (≥ 700 km/h). Time- and space-saving laboratory approaches are needed to test key electromagnetic components at relevant cruise and top speeds approaching the speed of sound. If successful, it could provide experimental evidence to support claims of feasible technical performances through magnetic suspension, guidance, and electromagnetic propulsion technologies at subsonic speeds. An example laboratory demonstrator that is suitable for testing the propulsion, guidance, and levitation technologies is shown in Figure 3. These types of wheeled designs were used previously to study maglev prototypes [37]–[40]. Earlier research investigated surface velocities of between 300 to 500 km/h while hyperloop targets even higher speeds. Argonne labs established a testing platform facility, as shown in the 1990s [41]–[43], but the testing was conducted only at much lower operating speeds. Recently, Hyperloop companies have also published testing reports. For example, Hardt Hyperloop reported on a similar propulsion test rig in 2023 and evaluated the performance of their LSRM design at speeds up to 300 km/h [23]. However, this tested top speed is not even half of the proposed hyperloop's cruise speed.

The alternative to using small-scale rotary-based test-stands is too costly to demonstrate the suspension and propulsion components at subsonic or near-sonic speeds along a long linear test track. An example of one of the most recent linear vehicle high-speed testing demonstrations was conducted by the TU Munchen Hyperloop team in 2019. They achieved a hyperloop speed record of 463 km/h at a pod design competition in low-pressure tube conditions without human passengers. In October 2020, Hyperloop One conducted its first human test with the Pegasus XP-2 two-passenger pod on a 0.5-km DevLoop track

outside of Las Vegas; they only reached a top speed of 161 km/h. These test tracks are too small to evaluate all the hyperloop performance characteristics. To achieve a hyperloop speed of 800 km/h with a 1G acceleration, a linear track of at least 4 km would be needed, not considering the distance needed for braking. For a more realistic acceleration of 0.1G or 0.2G, the required acceleration distance would be at least 39 km or 19 km, respectively.

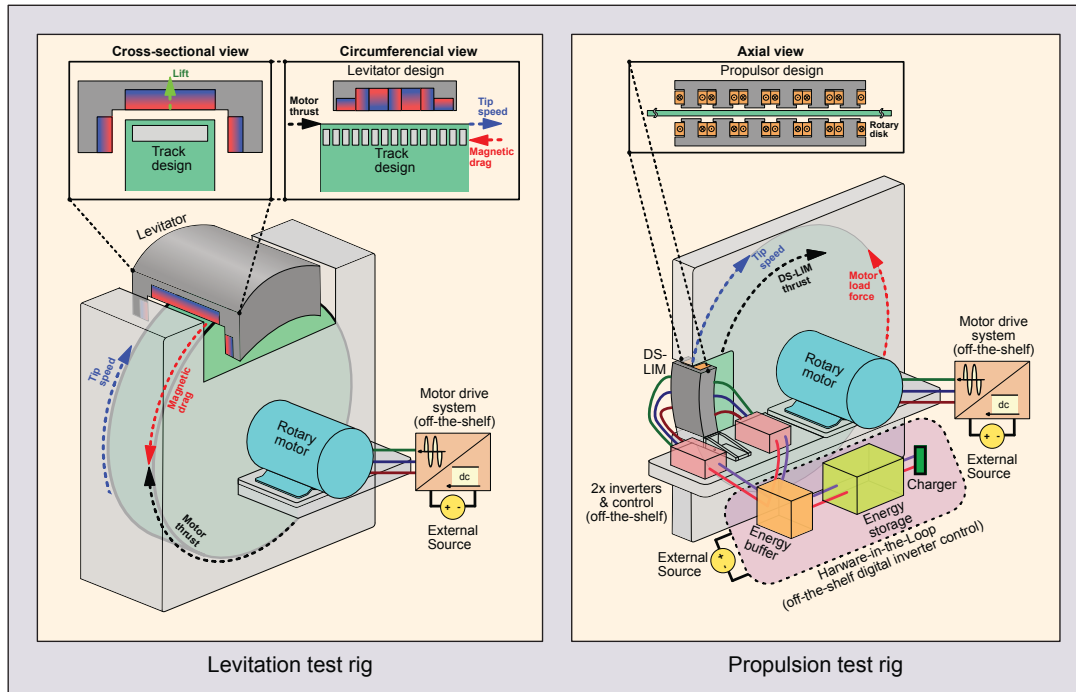


Figure 3 – Levitation and propulsion record player test rigs for assessing hyperloop levitation solutions.

To avoid the need for a long track, a rotary test bench approach is proposed to approximate the real application in Figure 3. In this approach, the track surfaces are transformed into the outer edge of the rotary disks in two record player arrangements. Using this setup, subsonic testing can be conducted in a safe, space-efficient, cost-effective, and convenient manner within the limitations of a small-scale laboratory at a university facility. Additionally, the testbench can be reused for rapid prototyping of the EDS levitator or the DS-LIM primary. Although the proposed laboratory arrangement has a stationary lift ski and propulsor while the track surfaces are in motion, opposite to the real-world application, they still replicate the same physical phenomena. The benefits of a large disk radius are that the rotational speed can be reduced for the same tip-speed, resulting in lower centrifugal forces and curvature.

As an example, a disk with a diameter of 1.77 meters can achieve a tip-speed of 1000 km/h at a rotational speed of approximately 3000 revolutions per minute (rpm), which is a practical high-speed condition of a rotary machine. Assuming turbulent flow with the disk placed in open air, an air density of 1.2 [kg/m³], and an air kinematic viscosity of $1.5 \cdot 10^{-5}$ [kg/ms], approximately 11.8 kilowatts (kW) is needed to overcome the air drag for a 10 cm thick disk. It is important to note that the electromagnetic behavior of subsonic experimental devices in Figure 3 will be similar with or without the soft-vacuum conditions proposed for the hyperloop. Therefore, a vacuum chamber will not be needed to evaluate the

electromagnetic performance. However, without a vacuum, significant power consumption would be needed to spin up the disk and sustain its surface velocity, resulting in extra power consumption. At reduced pressure, convective heat transfer would be replaced by radiation.

It is worth noting that the experimental approach presented in Figure 3 will be challenging to implement due to the difficulty in balancing rotors at such high angular speeds. Nevertheless, the types of general test platform facilities shown in Figure 3 would enable the testing of the core hyperloop components at much higher speeds (including subsonic and beyond) within a limited laboratory environment. Moreover, they could also be used to test alternative emerging passive propulsion and levitation concepts, such as electrodynamic wheels (EDWs) [30].

Table 2 shows how the disk’s rotational velocity changes as a function of the outer surface velocity. General Electric’s high-speed test setup reached 483 km/h with a rotational speed of 631 rpm. Its key specifications are listed in Table 3 and it is depicted in Figure 4.

Table 2 – Rotational speed as a function of outer surface velocity for a disk with a diameter of 1.77 m.

300 km/h	400 km/h	500 km/h	600 km/h	700 km/h	800 km/h	900 km/h	1000 km/h
900 rpm	1200 rpm	1500 rpm	1800 rpm	2100 rpm	2400 rpm	2700 rpm	3000 rpm

Table 3 – Specifications of General Electric’s high-speed, double-sided linear induction motor (LIM) test setup from 1975 [35].

Surface velocity	Disc diameter	Disc thickness	Airgap height per side	Motor length	Number of poles	Number of phases	Phase voltage	Electrical frequency
483 km/h	2.03 m	304.6 mm	12.7 mm	0.91 m	4	2 x 3	267 V	400 Hz

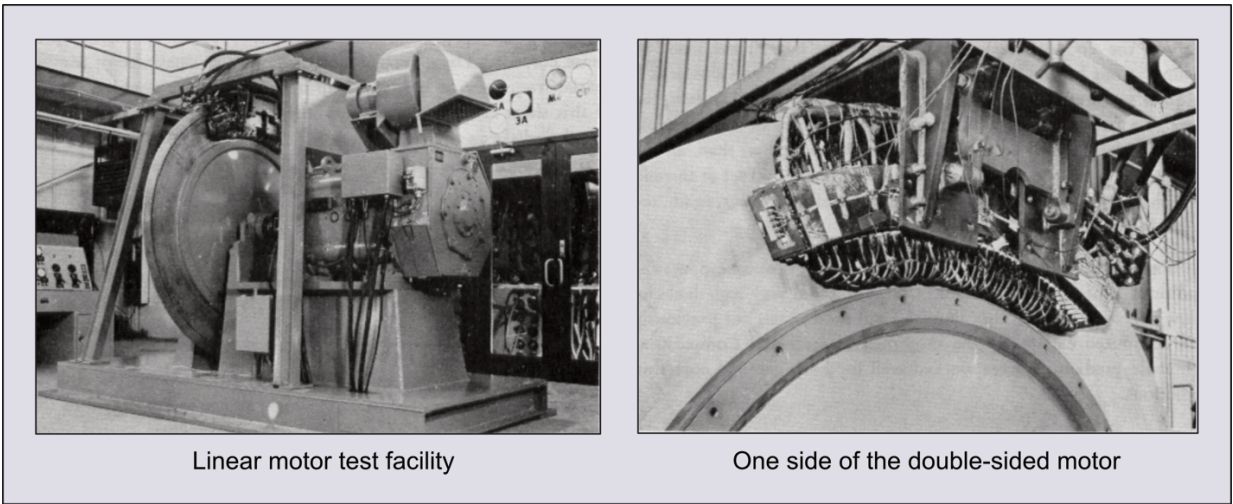


Figure 4 – Record-player test setup and the high-speed, 483-km/h, double-sided LIM from General Electric in 1975 [35].

An example of one of the largest reported maglev rotary test wheels was built in Canada with a 7.6-meter diameter, but it only reached surface velocities up to 100 km/h [44], [45]. Superconducting magnets were also used in the experimental studies.

Although many theoretical studies and simulations have been conducted on hyperloop propulsion and suspension technologies, experimental proof of their core concepts at subsonic speeds is still lacking. Developing realistic test setups that can be conducted in a space-limited laboratory is essential to test these technologies. According to a 2018 innovation report from the UK [46], critical short-term research and development needs for hyperloop include propulsion, levitation, energy storage, and thermal management, as well as the need for adequate testing facilities. Furthermore, the report highlights that electrotechnical research in the field of hyperloop is in its early stages and requires further development. While European governments have a high interest in the hyperloop, the efforts to develop the hyperloop in the US are more based on private funding. This funding appears to be reducing as the commercial and cost prospects for the hyperloop become less clear [15].

Conclusion and Outlook

After a decade of hyperloop development, there are still significant basic research needs that must be addressed in order to mature hyperloop's key maglev technologies. Much of the magnetic and electromagnetic cost challenges faced and never addressed by classical maglev approaches are going to be even more challenging when the hyperloop maglev vehicles operate at subsonic surface speeds.

We see significant hyperloop development going on in Europe, while maglev competencies are mostly based in Asia. Knowledge transfer is deemed essential to deal with the significant technical and cost challenges to realize hyperloop. Moreover, there is a lot of basic experimental research from the 1970s and 1980s that seem to have been forgotten in hyperloop development circles.

The development of hyperloop technology is still in progress, with different entrepreneurs and companies working on solutions that have not yet been tested at full-scale or at high cruise speeds approaching the speed of sound (≥ 700 km/h). Although hyperloop could be set to reshape the future of transportation, there are many problems that may hinder its realization. The futuristic concept is currently challenged by concerns of safety, engineering practicality, and economic feasibility.

Biographies

Jonas Kristiansen Nøland earned his Ph.D. degree in engineering physics from the Ångström Laboratory, Uppsala University, Uppsala, Sweden, in 2017. He is currently an associate professor in the Department of Electric Energy, Norwegian University of Science and Technology (NTNU), Trondheim, 7491, Norway, where he focuses on scaling up zero-emission propulsion systems. He is a Senior Member of IEEE and the IEEE Industrial Electronics Society and serves as an associate editor of IEEE Transactions on Industrial Electronics, IEEE Transactions on Energy Conversion & IEEE Transactions on Transportation Electrification.

Jonathan Z. Bird received the B.S. degree in electrical and computer engineering from The University of Auckland, Auckland, New Zealand, in 2000, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Wisconsin–Madison, Madison, WI, USA, in 2004 and 2006, respectively. From 2006 to 2008, he was a Senior Design Engineer with General Motors Advanced Technology Center, Torrance, CA, USA. He is currently an associate professor at Portland State University, Portland, OR, USA. His research interests include electric machine design, electromagnetics, and control. He is a Senior Member of IEEE and serves as an associate editor of IEEE Transactions on Magnetics

References

- [1] G. Medhurst, "Calculations and Remarks, Tending to Prove the Practicability, Effects and Advantages of a Plan for the Rapid Conveyance of Goods and Passengers: Upon an Iron Road Through a Tube of 30 Feet in Area, by the Power and Velocity of Air", DN Shury, 1812.
- [2] W. Heath, "March of Intellect", 1828, url: https://en.wikipedia.org/wiki/March_of_Intellect#/media/File:A_futuristic_vision_Wellcome_V0041098.jpg.
- [3] E. C. Goddard, "Vacuum tube transportation system", U.S. Patent No. 2,511,979, June 1950.
- [4] R. Palacin, "Hyperloop, the Electrification of Mobility, and the Future of Rail Travel", *IEEE Electr. Mag.*, vol. 4, no. 3, pp. 4–51, Sep. 2016, doi: 10.1109/MELE.2016.2584918.
- [5] W. Qin and J. Z. Bird, "Electrodynamic Wheel Magnetic Rolling Resistance", *IEEE Trans. Magn.*, vol. 53, no. 8, 8107407, Aug. 2017, doi: 10.1109/TMAG.2017.2693962.
- [6] V. Smil, "The Hyperloop is Hyper Old: Elon Musk Merely Renamed a 200-Year-Old Dream: Numbers Don't Lie", *IEEE Spectr.*, vol. 58, no. 12, pp. 18–19, Dec. 2021, doi: 10.1109/MSPEC.2021.9641774.
- [7] "EEA greenhouse gases - data viewer," *EEA – an agency of the European Union*, published 13 April 2021, url : <https://www.eea.europa.eu/publications/data-and-maps/data/data-viewers/greenhouse-gases-viewer>.
- [8] "Sustainable mobility – The European Green Deal," factsheet, *European Commission*, 11. Dec. 2019.
- [9] U. c. d. Leyen, "A union that strives for more – My agenda for Europe (2019-2024)," *European Commission*, 16. July 2019.
- [10] S. d. Keersmaecker & S. Meder, "Sustainable and Smart Mobility Strategy – putting European transport on track for the future", Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, *European Commission*, 9. Dec. 2020, url: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789>.
- [11] J. K. Nøland, "Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review", *IEEE Access*, vol. 9, pp. 28439–28458, Feb. 2021, doi: 10.1109/ACCESS.2021.3057788.
- [12] L. Mitropoulos, A. Kortsari, A. Kolliatos & G. Ayfantopoulou, "The Hyperloop System and Stakeholders: A Review and Future Directions", *Sustainability*, vol. 13, no. 15, Jul. 2021, doi: 10.3390/SU13158430.
- [13] K. Gkoumas, "Hyperloop Academic Research: A Systematic Review and a Taxonomy of Issues", *Appl. Sci.*, vol. 11, no. 13, Jun. 2021, doi: 10.3390/APP11135951.
- [14] K. Gkoumas & M. Christou, "A Triple-Helix Approach for the Assessment of Hyperloop Potential in Europe", *Sustainability*, vol. 12, no. 19, Sep. 2020, doi: 10.3390/SU12197868.
- [15] E. A. Taub, "Is Hyperloop Doomed", *N. Y. Times*, Sep. 2022, url: <https://www.nytimes.com/2022/09/22/business/hyperloop-transit-virgin.html>.
- [16] I. Rahman-Jones, "High-speed train company Hyperloop One shuts down", *BBC News*, Dec. 2023, url: <https://www.bbc.com/news/technology-67801235>.
- [17] M. Flankl, T. Wellerdieck, A. Tüysüz, and J. W. Kolar, "Scaling laws for electrodynamic suspension in high-speed transportation", *Electr. Power Appl.*, vol. 12, no. 3, pp. 357–364, Dec. 2017, doi: 10.1049/IET-EPA.2017.0480.
- [18] J. K. Nøland, "Evolving Toward a Scalable Hyperloop Technology: Vacuum transport as a clean alternative to short-haul flights", *IEEE Electr. Mag.*, vol. 9, no. 4, pp. 55–66, Dec. 2021, doi: 10.1109/MELE.2021.3115542.
- [19] M. Witt and S. Herzberg, "Technical-economical System Comparison of High Speed Railway Systems", *Proc. 18th Int. Conf. Magnetically Levitated Syst. Linear Drives*, pp. 86, 2004, url: http://www.maglev.ir/eng/documents/papers/conferences/maglev2004/topic1/IMT_CP_M2004_T1_11.pdf.
- [20] R. M. Borges and E. Quaglietta, "Assessing Hyperloop Transport Capacity Under Moving-Block and Virtual Coupling Operations", *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 12612–12621, Aug. 2022, doi: 10.1109/TITS.2021.3115700.

- [21] D. Tudor and M. Paolone, "Operational-driven optimal-design of a hyperloop system", *Transp. Eng.*, vol. 5, 100079, Sep. 2021, doi: 10.1016/J.TRENG.2021.100079.
- [22] Z. Long, G. He, and S. Xue, "Study of EDS & EMS Hybrid Suspension System With Permanent-Magnet Halbach Array", *IEEE Trans. Magn.*, vol. 47, no. 12, pp. 4717–4724, Dec. 2011, doi: 10.1109/TMAG.2011.2159237.
- [23] "Hyperloop Progress Paper", *Hardt Hyperloop*, pp. 1–24, Aug. 2011, url: <https://www.hardt.global/press/hardt-hyperloop-releases-open-technology-10-year-anniversary-elon-musk-paper>.
- [24] A. Cassat, M. Jufer, and Macabrey, "Swissmetro and transrapid comparison of the electromechanical components and the power supply in a specified vacuum tunnel environment", *Proc. 16th Int. Conf. Magnetically Levitated Syst. Linear Drives*, pp. 119, 2000, url: <https://infoscience.epfl.ch/record/166353>.
- [25] A. Cassat and M. Jufer, "MAGLEV projects technology aspects and choices", *IEEE Trans. Appl. Superconduct.*, vol. 12, no. 1, pp. 915–925, Mar. 2002, doi: 10.1109/TASC.2002.1018549.
- [26] E. Levi, "Field tests on a MAGLEV with passive guideway linear inductor motor transportation system", *IEEE Trans. Magn.*, vol. 9, no. 3, pp. 242–248, Sept. 1973, doi: 10.1109/TMAG.1973.1067639.
- [27] G. R. Slemon, "An experimental study of a homopolar linear synchronous motor", *Electr. Mach. Power Syst.*, vol. 4, no. 1, pp. 59–70, Mar. 1979, doi: 10.1080/07313567908955360.
- [28] I. Boldea, A. Trica, G. Papusoiu, and S. A. Nasar, "Field tests on a MAGLEV with passive guideway linear inductor motor transportation system", *IEEE Trans. Veh. Technol.*, vol. 37, no. 4, pp. 213–219, Nov. 1988, doi: 10.1109/25.31126.
- [29] E. R. Laithwaite, "Transport Without Wheels", *Westview Press*, pp. 160–178, 1977, url: <https://trid.trb.org/view/380795>.
- [30] Y. Hikasa and Y. Takeuchi, "Detail and experimental results of ferromagnetic levitation system of Japan air lines HSST-01/-02 vehicles", *IEEE Trans. Veh. Technol.*, vol. 29, no. 1, pp. 35–41, Feb. 1980, doi: 10.1109/T-VT.1980.23819.
- [31] E. R. Laithwaite, "A History of Linear Electric Motors", *Red Globe Press London, Macmillan*, no. 1, pp. 1–389, 1987, doi: 10.1007/978-1-349-08296-4.
- [32] J. Z. Bird, "A Review of Integrated Propulsion, Suspension and Guidance Passive Guideway Maglev Technologies", *Proc. Int. Symp. Linear Drives Ind. Appl.*, pp. 1–6, Jul. 2019, doi: 10.1109/LDIA.2019.8770983.
- [33] R. D. Thornton, "Flying low with Maglev", *IEEE Spectr.*, vol. 10, no. 4, pp. 47–54, Apr. 1973, doi: 10.1109/MSPEC.1973.5216848.
- [34] R. D. Thornton, "Magnetic levitation and propulsion", *IEEE Trans. Magn.*, vol. 11, no. 4, pp. 981–995, Jul. 1975, doi: 10.1109/TMAG.1975.1058781.
- [35] O. C. Coho, G. B. Kilman, and J. I. Robinson, "Experimental evaluation of a high speed double sided linear induction motor", *IEEE Trans. Power Appar. Syst.*, vol. 94, no. 1, pp. 10–17, Jan. 1975, doi: 10.1109/T-PAS.1975.31818.
- [36] W.-Y. Ji, G. Jeong, C.-B. Park, I.-H. Jo & H.-W. Lee, "A Study of Non-Symmetric Double-Sided Linear Induction Motor for Hyperloop All-In-One System (Propulsion, Levitation, and Guidance)", *IEEE Trans. Magn.*, vol. 54, no. 11, 8207304, Nov. 2018, doi: 10.1109/TMAG.2018.2848292.
- [37] Y. Cai, D. M. Rote, T. M. Mulcahy, Z. Wang, S. S. Chen, and S. Zhu, "Dynamic stability of repulsive-force maglev suspension systems", *Argonne National Lab.*, Argonne, IL, US, Report # ANL-96/18, 1996, doi: 10.2172/469111.
- [38] M. T. Thompson, R. D. Thornton, and A. Kondoleon, "Flux-canceling electrodynamic maglev suspension—Part I: Test fixture design and modeling", *IEEE Trans. Magn.*, vol. 35, no. 3, pp. 1956–1963, May 1999, doi: 10.1109/20.764892.
- [39] M. T. Thompson and R. D. Thornton, "Flux-canceling electrodynamic maglev suspension—Part II: Test results and scaling laws", *IEEE Trans. Magn.*, vol. 35, no. 3, pp. 1964–1975, May 1999, doi: 10.1109/20.764894.
- [40] D. Chu and F. C. Moon, "Dynamic instabilities in magnetically levitated models", *J. Appl. Phys.*, vol. 54, no. 3, pp. 1619–1625, Mar. 1983, doi: 10.1063/1.332147.
- [41] Y. Cai and S. S. Chen, "A Review of Dynamic Characteristics of Magnetically Levitated Vehicle Systems", *Argonne National Lab*, ANL-95/38, pp. 1–82, Nov. 1995, url: <https://apps.dtic.mil/sti/citations/ADA306209>.
- [42] Y. Cai, D. M. Rote, T. M. Mulcahy, Z. Wang, S. S. Chen, and S. Zhu, "Dynamic Stability of Repulsive-Force Maglev Suspension Systems", *Argonne National Lab*, ANL-96/18, pp. 1–79, Nov. 1996, url: <https://www.osti.gov/servlets/purl/469111>.
- [43] D. M. Rote and Y. Cai, "Review of dynamic stability of repulsive-force maglev suspension systems", *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 1383–1390, Mar. 2002, doi: 10.1109/20.996030.
- [44] D. L. Atherton and A. R. Eastham, "Canadian developments in superconducting Maglev and linear synchronous motors", *Cryog.*, vol. 15, no. 7, pp. 395–402, July 1975, doi: 10.1016/0011-2275(75)90005-3.
- [45] D. L. Atherton, A. R. Eastham, B.-T. Ooi, and O. Jain, "Review of dynamic stability of repulsive-force maglev suspension systems", *IEEE Trans. Magn.*, vol. 14, no. 2, pp. 59–68, Mar. 1978, doi: 10.1109/TMAG.1978.1059726.
- [46] V. Chesterton and K. Davies, "Hyperloop – Opportunity for UK Supply Chain", *Catapult Transport Systems*, Sep. 2018, url: https://cp.catapult.org.uk/wp-content/uploads/2021/07/Hyperloop_Report.pdf.