Experiencing Hyperloops: The Transit of the Future

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This article explores the hype about hyperloops, discussing technological aspects, passenger experiences, competing transit modes, and possibilities for a transportation revolution.

Through the centuries, travel has transformed to become faster and safer and provide passengers with a better experience. However, contemporary high-speed mass transit systems continue to have many drawbacks, including pollution (air and noise), congestion, and poor on-time performance. In this context, hyperloop technology is expected to represent a major change in the transportation sector.

In 2013, Tesla and SpaceX proposed an open source concept for building an ultrafast transportation system, namely, Hyperloop Alpha.[1] A demonstration of a hyperloop coach similar to Hyperloop Alpha occurred in 2019 in Spain, performed by Hyperloop Transformation Technologies (HTT) and Carbures.[4] Later, on 8 November 2020, Virgin Hyperloop (VH) successfully tested its design, Pegasus, while carrying passengers in the Nevada desert, where the floating pod reached 160 km/h in 6.25 s.[2,3] This article presents hyperloop technology and designs, reviewing their successes and challenges.

HYPERLOOP BASICS

A hyperloop is a novel high-speed mass transportation system. It has three major components: a tube, pod, and terminal. The tube is a large sealed, low-pressure system that can be constructed above or below ground. A coach runs inside this controlled environment and is often referred to as a *pod*. It is a vehicle that can carry passengers and goods. Inside, it is similar to an aircraft, with essentials such as seating, an oxygen supply, and a medical kit, and nonessentials including food and beverages, charging points, and lavatories.

The pod employs magnetic or aerodynamic levitation (using air-bearing skis) along with electromagnetic or aerodynamic propulsion to glide along a fixed

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guideway.[1,2,5] Friction between the pod and the ground is substantially reduced due to the levitation. The reduced barometric pressure in the tube accounts for the near-vacuum aerodynamic drag when the pod travels. Terminals are similar to railway stations and airports, facilitating arrivals and departures. Their design depends on security and loading requirements.[5]

HYPERLOOP COMPETITORS

There are four types of mass transportation systems: roadways, railways (for example, maglev trains, bullet trains, and monorails), waterways, and airways. Unlike these, hyperloops operate in a closed environment. This section highlights some of the functional high-speed systems that can compete against hyperloops.

Monorails

Monorails straddle a single beam that supports and guides them.[6] Most use electric motors, but diesel-powered versions exist. The Wuppertal Schwebebahn railway, in Germany, is one of the oldest and functional. Its route is approximately 13 km, and it carries an average of 85,000 passengers a day, with one coach accommodating around 180 people (through 48 seats and standing room). It has a maximum speed of 60 km/h, an energy consumption of 2.12 kWh/km (or 763,000 J/km) per 100 passengers, and a departure frequency of 6 min during rush hours and 15 min at off-peak times. Tickets cost €2.5 (US$3, as of March 2021) during the day. Such systems have limitations.[7] While monorails cost less than traditional trains when they are elevated, they are more expensive for surface and subway use. They cannot negotiate sharp turns because they begin to sway back and forth, and they cannot switch tracks as easily. These drawbacks make them uncompetitive against hyperloops (schwebebahn.de).

High-speed rail

High-speed rail (HSR) includes trains that travel 250 km/h or faster.[8] Operating since 1964, Japanese bullet trains (on the Tokaido Shinkansen route) represent the oldest HSR in the world and mostly run at a frequency of 2 trains/h. A reserved seat from Tokyo to Shin-Osaka on a Nozomi train costs 14,450 yen (US$135, as of March 2021). The trains offer first-class and coach seating, lavatories, charging ports, and food. Compared to HSR, hyperloops are envisioned to be less expensive, much faster, and more convenient, including on-demand service.[5] For instance, VH claims that two-way tunnel tubes would be smaller and less costly than one-way HSR tunnels (global.jr-central.co.jp/en/).[9]

Maglev

Maglev trains use magnetism to levitate and move, avoiding friction by eliminating wheels.[6] There are two types of levitation: active levitation (electromagnetic suspension) and passive levitation (electrodynamic suspension).[5] The former harnesses electromagnets' attractive force by frequently (multiple times a second) switching the magnets on and off. The latter uses vehicle-side permanent magnets or superconducting electromagnets and highly conductive guideway infrastructure that generates opposing fields through induction.

Maglev trains are the fastest in the world, with a recorded speed of 605 km/h, and widely used in Germany, China, and Japan. Shanghai Transrapid maglev trains hold 574 passengers and operate at a frequency of 4 trains/h.[10] A one-way ticket costs 50 renminbi (US$8, as of March 2021). The trains consume about 0.77 million J/passenger-kilometer.[10] Since hyperloops employ the same principles, they are often seen as extensions of maglev trains. In a later section, we will highlight the differences between the two technologies.

Airplanes

Airplanes are a hyperloop competitor, especially in terms of speed. For instance, a Bombardier CRJ700 jet has a capacity of 130 passengers, consumes roughly 2.1 million J/passenger-kilometer, and travels at a maximum speed of 876 km/h.[10] Although prices are highly variable, tickets tend to be expensive. Since not every location has an airport, air travel is often augmented by rail and road routes to final destinations. Unlike airplanes, hyperloops will be quiet.[5,11]

DESIGNS AND DEVIATIONS

Hyperloops have significantly evolved to reach their current form. There are major differences between the theoretical design presented in the 2013 Alpha paper[1] and the implementation of VH's Pegasus of 2020.[3] Diana Zhou, VH's market strategy manager, has described the challenges during the implementation and testing of the techniques in the Alpha paper.[2] The following includes a description of both designs (see Figure 1).

Hyperloop Alpha design

This hyperloop design[1] has four major components: a pod, a tube, propulsion, and a route. Safety and reliability considerations are outlined, including those related to accidents and power outages. The cost of building such a system with two one-way tubes and 40 capsules is estimated at US$6 billion,

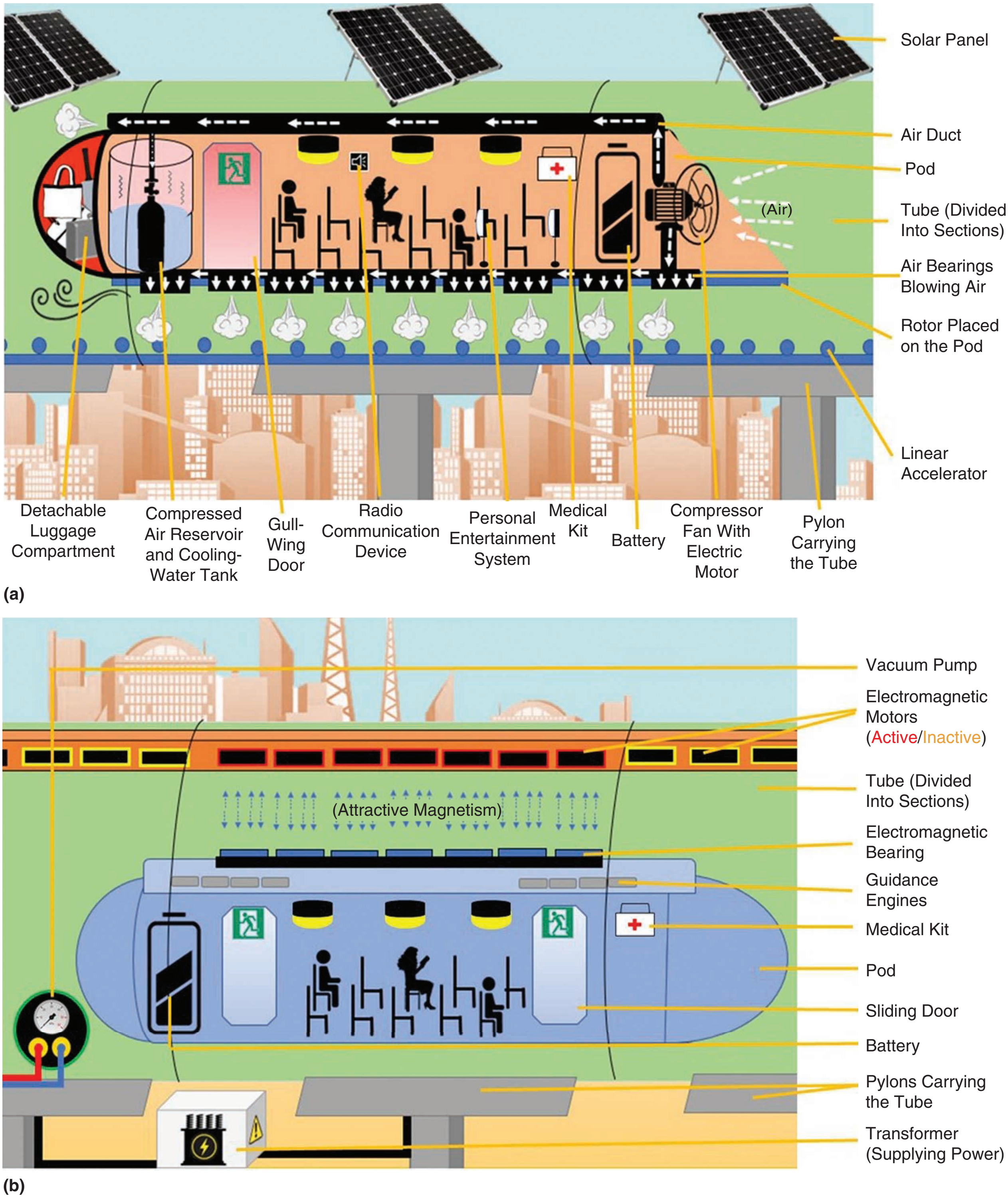

FIGURE 1. Hyperloop designs (not to scale). (a) An early rendering of Hyperloop Alpha.[1] (b) The VH hyperloop.[3,5]

which could be recovered within two decades. The one-way ticket price is estimated to be a sum of the base fare that would be US$20 and the operating cost to carry a passenger on the pod.

Two types of pods are described: "passenger" (P1) and "passenger plus vehicle" (P2). The former is 1.35 × 1.1 m and weighs 3,100 kg; it holds 28 passengers. The latter is larger, with a frontal area not exceeding 4 m^2 and a weight of 3,500 kg. It can fit three full-size automobiles as well as passengers. Both pods feature gull-wing doors and a luggage compartment in the front or the rear. Their expected achievable speed is 1,220 km/h. A pod traveling that fast would cover the 615 km between Los Angeles and San Francisco in 30–35 min, compared to 6 h by road. The average departure interval could range between 30 s and 2 min.

Costly maglev technology is discarded. Instead, 28 ski-like bearings at the bottom of the pods operate through compressed air and aerodynamic lift. This produces levitation and reduces fiction. The tube wall, made of steel, is 20–23 mm thick for P1 systems and 23–25 mm thick for P2. The air pressure inside the tube (which has a diameter of 2.23 or 3.3 m for P1 and P2, respectively) is around 100 Pa, which is very low compared to the mean sea level atmospheric pressure of 101,325 Pa and difficult to achieve. Two tubes are welded side by side, building each one-way route, with a 30-m distance between the pylons that elevate the structure.

According to the continuity equation, when fluid flowing through a tube experiences a reduction in the cross-section area, it rapidly speeds up to maintain the same mass-flow rate. This is known as Kantrowitz limit. In the case of hyperloops, the limit is the minimum ratio of the tube area to the pod area, below which the flow will choke. In Musk,[1] a compressor fan (with a compression ratio of 20:1) mounted to the nose of a pod is a feasible solution to the Kantrowitz limit. Powered by an electric motor (P1: 325 kW; P2: 365 kW), the fan transfers high-pressure air from the front to the rear. This provides additional propulsion and reduces air resistance. It also helps to create a low-friction system by directing most of the air to the air bearings. An onboard water tank cools the compressed air, producing steam that is stored until a terminal is reached. Both water and steam are replaced automatically at each stop.

For propulsion, pods have a round induction motor that is opened and rolled flat. An induction motor is composed of two parts: a stator (a stationary element that is 0.5 m wide and 10 cm tall and that weighs 800 kg/m) and a rotor (a moving element with an aluminum blade that is 15 m long, 0.45 m tall, and 50 mm thick). The rotor is installed on the pod, and the flattened stator installed in the tube works as a linear accelerator. The rotor and linear accelerators are 20 mm apart. Accelerators are installed approximately every 110 km to provide momentum to the rotor and propel the pods.

Terminals (stations) are isolated from the tube to limit air leakage. A terminal is constructed at each end of the tube, with an estimated average capacity of 840 passengers/h. Insights into terminal management are provided in Musk,[1] Stubbin et al.,[5] and Covell.[12] Terminals have platforms similar to railway stations. Each platform has an airtight chamber, called an air lock, with a gateway opening onto the platform and another opening into the tube. Once passengers board, a pod is pushed to the chamber, and both the gateways will seal. The chamber's pressure will be reduced to match that of the tube. The gateway to the tube will open, and the pod will depart. Events during a hyperloop journey appear in Figure 2.

Covell[12] summarizes hyperloop energy economy. Electricity is required for the linear accelerators, pod battery, vacuum pumps, lighting, air conditioning, and so on. Hyperloop Alpha's needs are satisfied by solar arrays placed above the tube. The average energy consumed by the Alpha system is projected to be 21 MW. Musk[1] claims that the solar panels (costing US$210 million for P1 and US$490 million for P2) can produce an annual average of 57 MW. Pods and most of their components are powered by batteries, which are replaced at each stop and charged at the terminals. Not much has been discussed about the energy economy of underground hyperloops, which cannot use solar panels. Although Alpha was a ground-breaking design, some aspects did not work well when tested by various research and development companies.[5] Nevertheless, the design acted as a catalyst for technological developments and established the framework for the first successful hyperloop, implemented by VH.

VH design

VH (formally Hyperloop Technologies, Hyperloop One, and Virgin Hyperloop One) was founded after the Hyperloop Alpha paper was published in 2013. The company built the world's first full-scale hyperloop test track, which opened in 2017.[2] The tube extends 500 m, with a 3.3-m diameter and a constant internal pressure of 100 Pa.[4] Since some parts of Alpha did not work well, design alterations were made.[9] For example, maglev technology is used in place of the aerodynamic levitation suggested by Musk.[1]

According to VH, air bearings consume an extreme amount of energy and raise the pods to a height that is insufficient for long distances.[9] Hence, VH developed indigenous maglev technology powered by onboard batteries. This attracts pods from the top, obtaining a passive track. Engines are placed on either side of the pods.[13] They have a 50% more compact motor with a 50% better power factor and generate a cruising velocity of 1,000 km/h in fewer than 5 min. Pods are propelled by a linear induction motor on the track and controlled by software that supplies energy for a fraction of a second when vehicles cross a motor, reducing energy consumption.[9] Similar to trains, pods start with 0.20 g of acceleration and encounter no turbulence.[13]

VH[13] says its hyperloop uses 10 times less energy per passenger-mile than a modern jetliner. Compared to the fastest conventional maglev train, which travels at half a pod's speed and consumes 33% more energy, the system requires approximately 75 Wh/passenger-kilometer. Electric cars traveling at 96.5 km/h consume more energy than VH pods moving at 805 km/h. Because it is completely electric, the system can draw power from any available source, and it produces no direct emissions.[13]

Setting hyperloops apart

Besides the design features reviewed so far, hyperloops have numerous attributes that distinguish them from traditional and high-speed mass transit systems. To start with, their backers claim hyperloops are the fastest, most energy-efficient mode of transportation, requiring "only 45 MJ of energy per passenger per journey."[12] Unlike competing systems, tubes are immune to heavy rainfall, hailstones, and snow as well as low-intensity natural disasters such as floods. HSR tracks require expansion joints to accommodate thermal expansion and contraction and are susceptible to earthquakes, while hyperloops include no rails and could be engineered for maximum resistance, with pylons that flex during tectonic events[1] and tubes made of small, modular sections.

Evolution with implementation

Recent work[14] includes two techniques for implementing hyperloops: the lightweight capsule solution and the low-infrastructure solution. The former involves an electrified tube to propel the pods and demands a higher initial investment, thereby limiting it to short distances. In the latter, pods propel

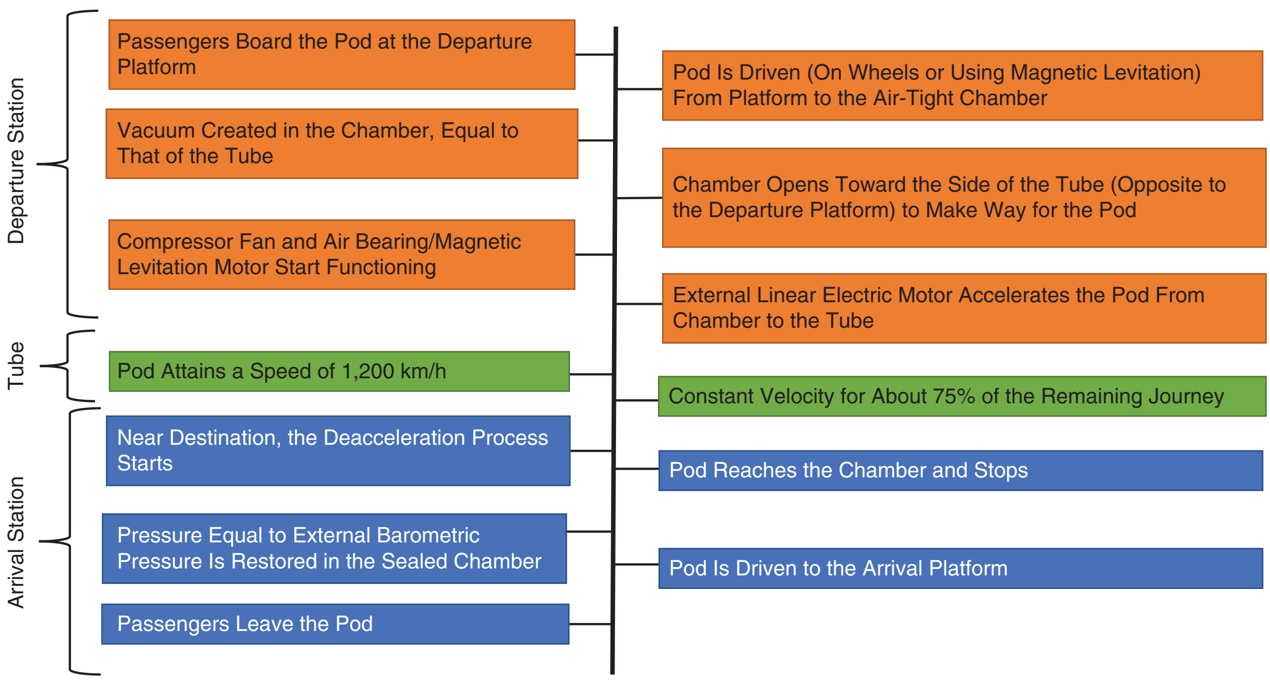

FIGURE 2. Technical events during a hyperloop journey.

themselves, which is cheaper to build and works better for long distances.

AECOM interviewed experts from various companies working with hyperloop technology and presented important developments in a preliminary feasibility report in March 2020.[5] The companies plan to use 3- and 5-m-diameter tubes made of steel, reinforced concrete, or both. Their pods are expected to weight around 20 tons and have a capacity of 47 passengers. Pods would have an average headway of 120 s, equating to 1,500 passengers/h. Substations to connect hyperloop components with the main grid and vacuum pumping stations would likely be installed outside the tubes at semiregular intervals. The substation total and intervals would vary depending on system configurations and pod frequencies. Vacuum pumping stations, however, would probably outnumber substations. The linear motor for propulsion could be installed in the tubes or on the pods.[5] While the former requires a high-power grid connection, the latter demands larger onboard batteries. Thus, this choice will greatly influence installation and operating costs, energy consumption, and system control strategies.

POSSIBILE BENEFITS

Musk[1] has discussed hyperloops' anticipated benefits. They include using less land than conventional railway tracks to cover equal distances, a structural design that is more resilient to earthquakes, and energy neutrality through the use of solar power.[5] Hyperloop innovations could be used to improve other transportation technologies. For instance, the maglev system developed by VH is inexpensive and energy efficient and could perhaps improve maglev trains. Furthermore, there is no possibility of human, wildlife, vegetation, vehicle, and other obstructions in hyperloop tubes. Hyperloops are designed to be energy self-sustainable, with a zero-carbon footprint.[12]

CHALLENGES

Evolving technologies such as hyperloops often face challenges. For instance, enormous investment capital must be raised, and land must be acquired, likely extending through multiple jurisdictions. Since a hyperloop cannot become functional in phases, many obstacles must be simultaneously surmounted. If the tube is underground, the soil texture, water table, and other geographical parameters might vary across the route; hence, such factors must be accounted for during planning. The expansion and contraction of the tube material because of temperature variations can challenge designers.[12] Interruptions for battery charging might require more convenient solutions.[5]

Tube depressurization is a major technological concern,[14] specifically, failing to create a large-scale vacuum system with current technology. Two depressurization scenarios were considered during the VH design process.[9] During small losses, pods will experience moderate drag, travel more slowly, and consume more energy. In serious events, pods will come to rest, and passengers will be immediately evacuated. Once the pressure is created and maintained, it can also be dangerous. It is so low that if exposed, humans could suffer severe hypoxia and other traumas.[10]

If a long tube is elevated, the pods' high speed can increase the dynamic amplification factor, easily exposing the structure to damaging vibrations.[5] Research is required to analyze whether a tube design with gaps, suggested by Musk,[1] to provide room for motion during earthquakes can be of any help. Unlike roads and railroad tracks, tubes cannot include curves.[12] Hyperloops reportedly generate static magnetic fields that can result in significant electromagnetic noise.[5] The materials to build the systems (such as steel) may pose challenges. In addition, it has been suggested to install metallic shells around pods to tame the electric field inside the vehicles.[5] However, this would add weight and cost.

Hyperloops are more likely to be accepted and successful when connecting densely populated areas via sparsely populated routes and where abundant land is available. Otherwise, their construction might displace residents and hurt biodiversity. They are expected to have their greatest viability at distances of fewer than 1,500 km, beyond which supersonic air travel is likely to be more convenient.[1] A preliminary report for the Canadian government[5] raises financial concerns and suggests the need for public–private partnerships to deploy the systems.

Safety standards are another difficult area. Initially, there was concern about how gravitational forces would affect passengers during sudden accelerations from zero to 1,000 km/h. However, this was resolved with the first human passenger trial.[3] In fact, the human body can tolerate an acceleration that is half the gravitational force at mean sea level (that is, $9.81/2 = 4.9\ m/s^2$).[4] Nevertheless, the industry will have to make considerable efforts to implement safety standards and improve hyperloops' social acceptance.

Standardization is a challenge, too. The limited availability of literature that discusses sensitive commercial components hinders policy makers' efforts to develop legislation.[5] Governments need to sponsor, develop, and procure such information, which takes time. On the other hand, immediate policy support is essential to accelerate technological development at the commercial level. This is a vicious cycle that hampers the production and deployment of hyperloops for public use.

WHERE DOES THE WORLD STAND?

The world is not too far from its first functional hyperloop. In 2017, The Boring Company was founded to dig hyperloop tunnels at a rapid pace.[4] It proposed plans to construct a tube connecting Washington, D.C., and New York City, with pods making the trip in about 30 min.[11] Similarly, VH wishes to collaborate with big engineering, construction, and transportation players to expedite hyperloops for public use.[15] Its initial plan was to build a network of tubes for pods gliding at 965 km/h.[3]

The European Union established a commission to craft hyperloop regulations.[5] A commercial feasibility study[10] was conducted for NASA in 2016. The Non-Traditional and Emerging Transportation Technology Council and the U.S. Department of Transportation issued guidelines for hyperloop regulations in July 2020.[16] Gulf countries view hyperloops as an opportunity to unify their economies.[11] In fact, the World Economic Forum identifies hyperloop-based transportation as one of the top 20 markets of tomorrow.[17] Start-up companies do not want to miss this opportunity, either. For example, HTT was formed through crowd collaboration to develop a hyperloop concept. Other hyperloop firms include DGWHyperloop of India and the Canadian company TransPod.[11] Many countries have plans to establish hyperloop networks. In 2017, the French government inaugurated a hyperloop research center in Toulouse to encourage research in the field through a public–private partnership.[4] In 2018, HTT and Abu Dhabi-based Aldar inked a deal to work on a 150-km project.[11] Potential routes include Mumbai–Pune, Delhi–Chandigarh, Bratislava–Brno, and Vijaywada–Amaravati.[4]

Testing is now underway.[5] Most of the privately funded companies, such as TransPod, Hardt, and Zeleros, use small-scale prototypes to explore potential challenges. Others, such as VH, are working on full-scale testing facilities. Much like maglev trains, hyperloops require testing facilities of at least 15 km.[5] In addition, the facilities must evaluate high-speed tube switching, emergency deceleration procedures, and evacuation plans.

PREDICTING THE PASSENGER EXPERIENCE

As a potential passenger, it is instinctive to envision possible experiences with hyperloops. Until now, the focus has largely been on conceptual proofs and testing as opposed to the interior designs of pods, which will define the passenger experience and which, based on current developments, we have tried to predict. The factors we considered are classified into two categories: core and peripheral.[18] Although core factors reside at the heart of production planning, an equal emphasis is required for peripheral ones to produce best experience.

Core factors

The core factors include the following:

- *Ticket prices*: It is claimed that hyperloops will be one of the most inexpensive modes of transportation between Los Angeles and San Francisco, with a one-way base fare of US$20.[12] However, depending on development costs, ticket prices may be higher.
- *Schedules*: As suggested by Camacho et al.,[19] flawless real-time schedule tracking and the frequency of service are important for passenger satisfaction. SpaceX and VH expect pods to depart every 2 min and on demand.
- *Placement*: There is a question about whether tubes will be built on the ground, on pylons, or in underground tunnels. The answer depends on location, which is similar to metropolitan rail networks. For example, Hong Kong is a group of islands, and an underground transit system may work better. Delhi is a densely populated city, so a combination of underground and elevated routes may be preferable.
- *Baggage*: In general, airplanes have limitations for luggage weights and sizes, while railways have size restrictions. A pod must levitate to eliminate friction. Therefore, baggage size and weight restrictions should be expected. However, it remains to be seen whether hyperloop companies will be able to facilitate bags as large as those permitted on flights. Another question is whether passengers would be allowed to carry their luggage with them.
- *Power failures*: Hyperloops are expected to be safe, even during power failures. Since pods are battery powered, they should be unaffected. Besides, the linear accelerators are expected to store enough energy to propel pods

to their destinations. For further safety, every pod will have mechanical brakes. VH's Devloop facility contains emergency exits every 75 m.[13] Regulators ought to define specifications for oxygen reserves to ensure safety during primary system failures.

- *Medical emergencies*: Like other public and private transportation, hyperloops must facilitate medical emergency preparedness. Radio communication devices should be used to inform the nearest destination that a patient will be arriving, and a first-aid kit should be available for immediate use inside pods.[1] With airplanes, there is a considerable delay when a flight has to perform an emergency landing. Hyperloops are expected to deliver passengers for medical assistance in less time.
- *Control*: Pods are expected to be driverless because all their functions will be governed through software. The system will be completely autonomous, although onboard attendants cannot be ruled out.

Peripheral factors

The peripheral factors include the following:

- *Integration of public transport systems*: Integrating bus, train, and aircraft systems with hyperloop networks would provide a seamless experience.
- *Boarding buffers*: People are required to arrive at airports 2–3 h before their flights. This is generally not the case with trains. For hyperloops, domestic travel is expected to be similar to the riding subways, trains, and trams. The time it takes to pass security checks, however, will largely decide the preboarding wait time. Ticketing and baggage tracking are expected to be electronic, making them simpler and faster than in airports.[1]
- *Environmental impacts*: Countries worldwide have initiated steps to become carbon neutral, if not carbon negative. For instance, Dubai and Abu Dhabi aim to reduce their carbon emissions by 75% by 2023.[11] It is essential that hyperloops be carbon neutral and energy self-sufficient. However, the impact of hyperloop construction could be a concern.
- *Lavatories*: Many users will expect lavatories in pods, although that is not apparent in current designs. Accommodating restrooms will require trials of passenger movements, similar to airplanes.[13]
- *Leisure*: The transportation industry aims for "journeys that passengers look forward to."[19] As with first-class travel, hyperloop accommodations at higher fares are expected. They may include TV screens, Internet access, food and beverages, special seats, and so on. Passengers may be provided with personal entertainment systems.[1]
- *Interference*: The electromagnetic noise that hyperloops generate may interfere with wireless devices, such as phones. Installing metallic shells to mitigate the noise may cause further inconvenience.

Recent innovations in high-speed transportation are providing mobility that is affordable, autonomous, and more enjoyable. Mass transportation reached another milestone with successful trials of hyperloops carrying passengers. This article presented the technical details of hyperloops and described related efforts that are underway, and it discussed possible passenger experiences. With all its advances and despite the challenges, hyperloop technology will considerably impact us in the foreseeable future.

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