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Additional Information

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TODAY, EVACUATED-TUBE transport (ETT) systems, also referred to as *hyperloops*, are becoming ever more famous.

They consist of a ground-based network enclosed within a tube in which the atmosphere can be controlled. If the air inside the tube is evacuated, a low-pressure environment is created and aerodynamic resistance can be reduced, enabling higher speeds and efficient energy consumption. A hyperloop adds one element to an ETT: levitation. As a result, no ground resistance exists, overcoming one of the major limitations of traditional trains.



# Evacuated-Tube, High-Speed, Autonomous Maglev (Hyperloop) Transport System for Long-Distance Travel

An overview.

## Origins of ETT

The history of ETT begins more than 200 years ago when, in 1799, English inventor George Medhurst proposed moving passenger carriages through a tunnel by using variations in pressure levels. Systems were built in France, England, and Ireland during the 19th century and called “atmospheric railways.” Even then, people were concerned about ETT, as demonstrated by Figure 1.

A century later, in 1904, Robert Goddard, at Worcester Polytechnic Institute, Massachusetts, combined the concept of airless tunnels to reduce resistance with the idea of magnetic levitation (maglev) systems to reduce ground friction losses. This could enable very high speeds with relatively little power for propulsion. Russian inventor Boris Weinberg built his first model, in 1909, at Tomsk University. During the following years, the evolution of both technologies (low-pressure tubes and maglev systems) advanced in parallel. The development of the first superconducting levitation technologies and linear motors led to the creation of maglev trains. Concurrently, advances in space and pipeline construction resulted in the development of high-volume vacuum systems, whose preeminent example is the Large Hadron Collider,

**Although hyperloops were proposed more than a century ago, they have become famous only during the past six years, due to a need to develop their technologies.**

with a total of 104 km of piping under vacuum.

In the late 1970s, Prof. Marcel Jufer, from Switzerland, combined pressure and magnetism, proposing Swissmetro to operate at pressures at which the Concorde SST was certified to fly, but no operational line was implemented. In August 2013, American businessman Elon Musk published an online whitepaper, “Hyperloop Alpha,” with a concept for air bearings for levitation and linear motors for propulsion at every station. In 2015, Musk’s SpaceX organized a university competition for students around the world to share ideas to boost hyperloop evolution. The idea

was to develop an annual event to motivate the development of innovative ideas and recruit the best students for the company.

From 2015, hyperloop companies arose globally to develop such a system, and cooperation agreements have been announced to enable international standards ensuring interoperability. During this time, a team at Universitat Politècnica de València (UPV), Spain, Hyperloop UPV, was created. It aimed to compete against top technological universities around the world and develop a hyperloop. After winning two prizes for its first prototype (best overall design and best propulsion system), it decided to go one



**Figure 1.** A satirical cartoon from an English newspaper in 1828, showcasing transport inventions. [Source: Reproduced under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) license. © The Trustees of the British Museum.]

step further and create Zeleros, an independent company. Its hyperloop concept appears in Figure 2.

## Key Benefits of Hyperloop Transportation Systems

### Why Now?

Although hyperloops were proposed more than a century ago, they have become famous only during the past six years, due to a need to develop their technologies, including the following:

- ▶ **Vacuum:** Hyperloops require large vacuum chambers. Today, the Large Hadron Collider, which began operation in 2009, accounts for 54 km of ultrahigh vacuum (around  $10^{-10}$  mbar).
- ▶ **Maglev:** The first maglev train operated at the Birmingham, U.K., airport from 1984 to 1995. The technology is sufficiently mature to facilitate high-speed maglevs in China and Japan.
- ▶ **Control:** High-frequency automation has been put to the test in several applications, such as the reusable Space X Falcon rocket, which is able to land vertically after completing a mission.
- ▶ **Composite and intelligent materials:** These enable building light and extremely resilient fuselages.
- ▶ **Power electronics and drives:** These devices are well developed, but there is still a wide margin for improvement in the railway sector. Progress is occurring in the automotive industry and aviation, where there are clear advances through projects such as the E-Fan X from Airbus.

Apart from technology, the necessity of a new means of transport is becoming more and more evident. Trends show ever-lengthening travel distances, particularly where high-speed trains and planes share or overlap markets. Air space congestion is especially worrying. By 2050, Airbus expects the number of flights to increase 100%. Eurocontrol, the organization that manages the air space in Europe, says in one of its reports, “For the future, with the saturation of airspace resources in the long-term, the congestion problem cannot be overcome unless the airspace structure is reorganized.”

In addition, as 21st century systems, hyperloops would be the greenest means of transportation: they are fully electric and hence have zero direct emissions. Thus, they are proposed as a solution to transportation saturation, as they would form a complimentary transport layer that can contribute to reducing pollution. Demand for air travel will continue growing. Deploying hyperloops could alleviate congestion by adding ground systems with performance similar to that of airplanes.

### Description of a Hyperloop

As described, hyperloops have several advantages. On the one hand, they are based on levitation. Thus, high-speed railway problems, such as wheel hunting and expensive rail maintenance, can be resolved, and efficiency can be improved. Apart from that, the partial vacuum inside the tube reduces the aerodynamic drag on a train. Also, the elimination of friction enables these systems to be as fast as planes, with the sound barrier as the theoretical limit (around 1,250 km/h).

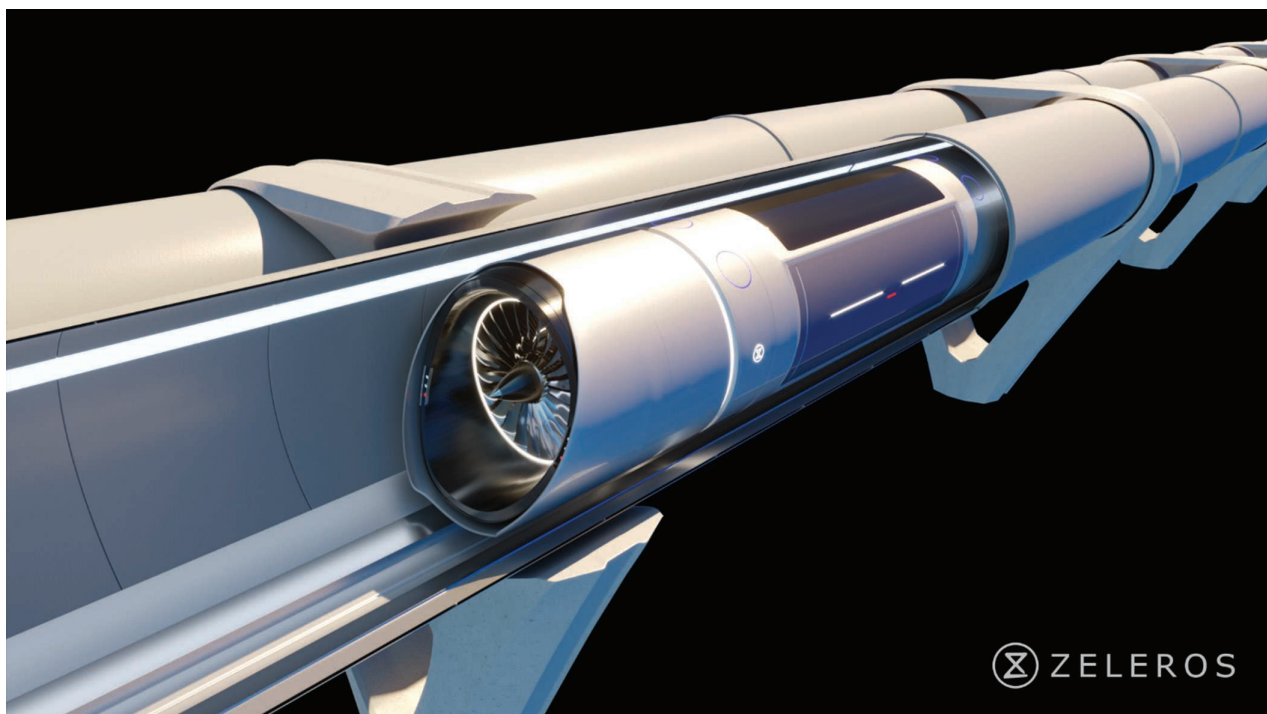


Figure 2. Zeleros's hyperloop.

That is twice the fastest speed obtained by high-speed rail and maglevs and similar to that of most fighter jets, with considerably less energy consumption (see Figure 3). Tubes also offer protection from adverse weather conditions. Crosswinds, heavy rain, and snow would have less impact on hyperloops. Numerous approaches have been taken to develop hyperloops, and several companies have emerged. Zeleros is one of them, whose approach is described in the “Description of Zeleros’s Hyperloop” section.

One of the drawbacks of hyperloops could be the amount of energy consumed by the pumps to maintain low pressure inside the tube. On the other hand, assuming that electric power of 40 W/m<sup>2</sup> can be extracted from solar panels and that the tube can be encased in panels, a 4-m diameter tube would produce 160 kW/km, which is, for an initial computation, more than enough to energize the pumps in a realistic scenario. Finally, the vehicles will be autonomous. This enables operation from a control center, eliminating the human factor from safety concerns and helping to reduce operating costs, including long training periods, simulators, and manuals.

### Description of Zeleros’s Hyperloop

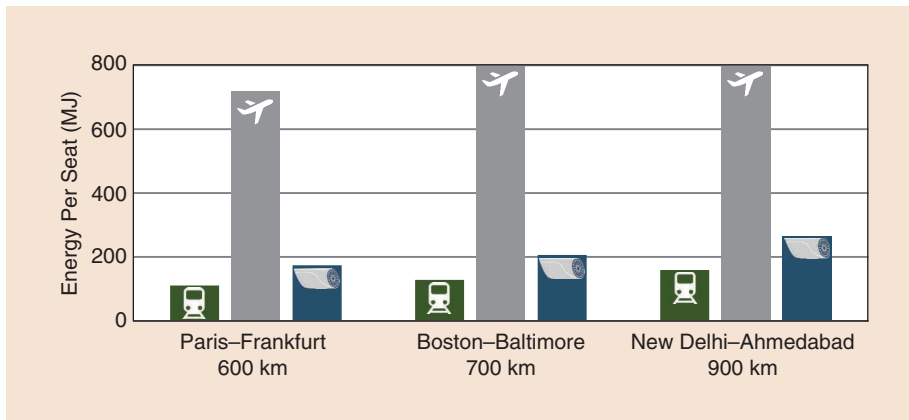
The Zeleros concept (Figure 2) can be divided into two systems. The levitation is based on hybrid electromagnetic suspension. Permanent magnets surrounded by electromagnets are placed on the vehicle. They lift the weight of the vehicle, while the electromagnets control the gap between the vehicle and tube wall. This way, less power is required to energize the coils, as most of the work is done by the permanent magnets. On the other hand, the main propulsion is based on a simplified aeronautical engine from which the combustion chamber has been removed. A compressor driven by an electric motor captures the air in front of the pod, compresses it, and exhausts it through a nozzle to generate the required thrust.

One of the main advantages is that, as all the technology is integrated into the vehicle, the track complexity is significantly reduced compared to other approaches that base their propulsion on linear motors. Since no coils and permanent magnets are required on the track, the infrastructure costs considerably less. Another benefit is that excess energy in the flux can be recovered using a turbine, making the whole system more efficient.

Regarding speed, there is a debate not only from the

technical perspective but also from the customer and user point of view. At a minimum, any transportation system added to the current portfolio needs to provide better service than existing ones. The fastest means of travel for conventional passengers is the airplane. In addition, it is well known that commercial airplanes are the safest mode of transportation. So, hyperloops should at least match airplanes in these two features. The problem to be solved is not what a hyperloop’s top speed would be but what its average speed would be for a given corridor.

An example of airplane average speeds can be found in Table 1; it demonstrates that despite having top speeds of 850–950 km/h, planes’ average speed (their so-called true speed, which includes taxi travel time), is much lower, as graphed in Figure 4. Considering this, there is a case to be made for a ground system that can sustain a cruising speed of at least 650 km/h for distances



**Figure 3.** The energy consumption per seat for different transport modes (one way). (Sources: Siemens and Flight Aware.)

Destination	Distance (km) (Straight Line)	Distance (km) (Actual Flown)	True Speed (km/h)	Real Travel Time (Including Taxi)
Toulouse, France	267	332	398	53 min
Paris, France	828	900	452	1 h, 48 min
Brussels, Belgium	1,085	1,259	567	2 h, 7 min
Amsterdam, The Netherlands	1,243	1,378	498	2 h, 26 min
Copenhagen, Denmark	1,771	1,996	591	2 h, 57 min
Stockholm, Sweden	2,317	2,530	680	3 h, 32 min

at which it remains competitive with planes (fewer than 3 h). What if the cities in the table were linked through a single hyperloop main line? The issue is whether it is preferable to take a 3-h, 30-min flight from Spain to Sweden or a 4-h hyperloop ride, assuming a sustained 650 km/h. This example does not factor in time spent in stations and airports, which has become a drawback to air travel, and it does not consider the fact that hyperloop stations could be placed in city centers. Safety will be discussed in more detail in the following, but a quick note is that hyperloops require no takeoffs and landings.

### Electric Propulsion for Hyperloops

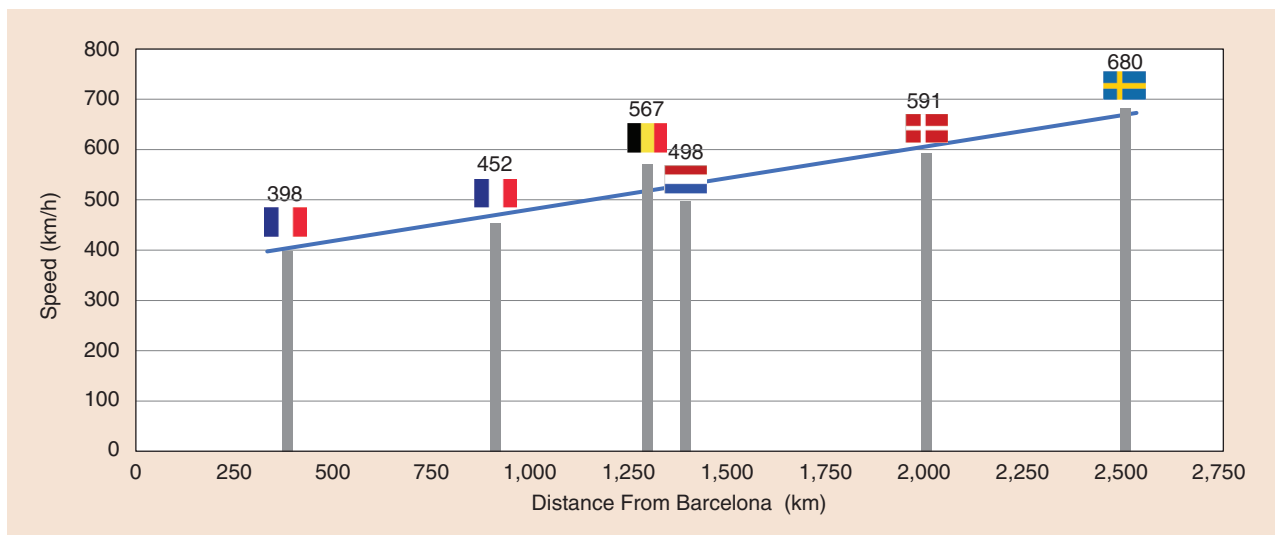
As explained, hyperloops are based on vehicles on closed tracks in low-pressure tubes that minimize energy consumption while operating safely and reliably. The purpose of the propulsion system is to achieve this and overcome the natural drag that the fluid inside the track exerts on the vehicles and other resistance, such as magnetic drag. The vehicles will transmit kinetic energy to the surrounding fluid, dragging a wake behind them. If the pod velocity is high enough, shock waves will occur, similar to those that take place in a high-speed train tunnel. However, shock waves in hyperloops cannot be released into the atmosphere, as they are for trains. They will bounce back and forth, hitting the vehicles and potentially jeopardizing stability.

Several hyperloop concepts use linear motors all along a route in a complete vacuum tube to avoid this effect. That level of vacuum may require a more complex and delicate two-stage pump. The high vacuum is required to create conditions where there is no aerodynamic drag. Nevertheless, the adverse effects of atmospheric pressure inside the tube can be overcome with a potentially better solution, an electric turbofan-like propulsion system. Turbofan engines, which are the most common for short-, medium-, and

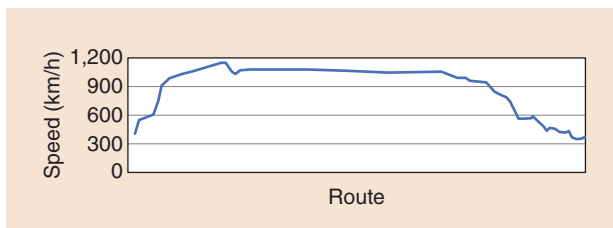
long-haul aircraft, are following the road map of other traditional propulsion systems, such as cars. Car engines, where mechanical power was traditionally generated by burning a hydrocarbon fuel, are being replaced by electric power units fed from batteries. Turbofan engines with electromechanical power units have the advantage of producing no emissions. This enables their use in confined facilities without incurring recirculating gas problems.

The use of an electric turbofan-like system is mandatory when the pressure inside the tube is at nonspace vacuum levels, which is basically due to vehicle aerodynamic drag. This system has two main effects: first, there is a way to cope with the piston effect. Air is transferred after a compression–decompression cycle from the front to the tail of the vehicle. Second, a propulsion system based on compressed air is obtained, compensating for the higher drag. A value of 10 kPa is enough to reduce the aerodynamic drag by more than one order of magnitude and enables the compressor to properly operate.

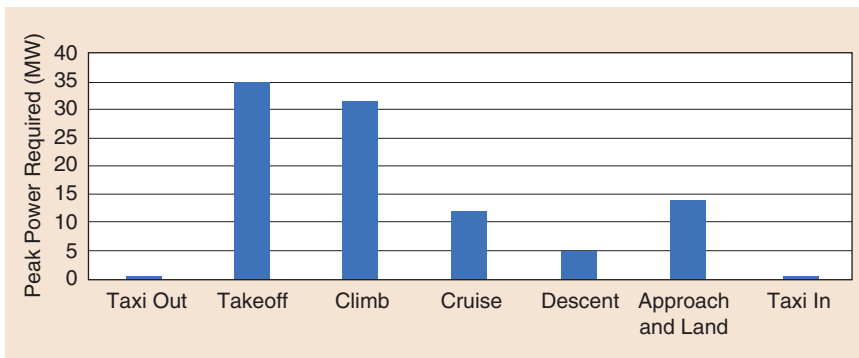
Electric turbofan systems have a disadvantage in that they are fit to operate only at their design point in an enclosed environment. However, at the design point, hyperloops are extremely competitive from an energy efficiency point of view, compared to aircraft and piston engine vehicles, which operate outside their design conditions for significant amounts of time. For short-haul routes, meaning fewer than 1,500 km, an aircraft is at its cruising speed for only about 70% of the distance (Figure 5). The efficiency of a system with such a characteristic is quite poor. Considering energy, a significant portion is wasted, especially during taxiing, takeoffs, and climbing (Figure 6). Hyperloops have the advantage that for routes in this range, they can reach their travel speed and maximum efficiency without a phase equivalent to climbing, which increases their cruising phase to approximately 95% of a trip.



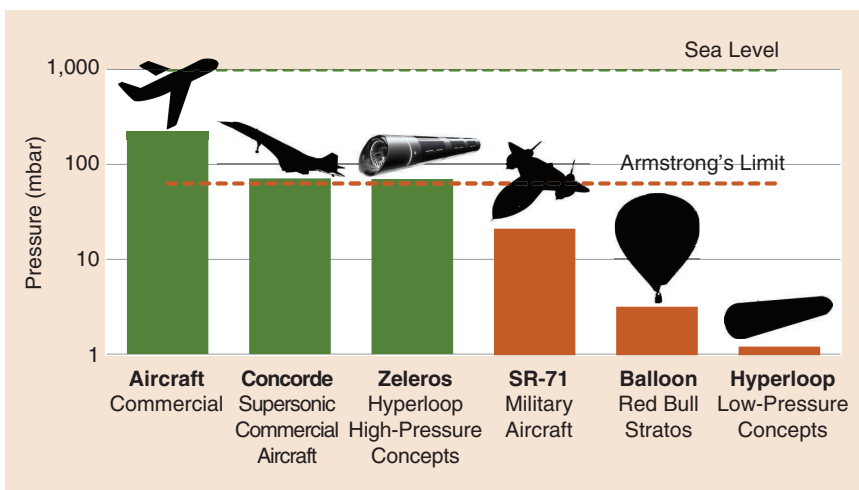
**Figure 4.** The true speed of flights from Barcelona, Spain, operated by Vueling Airlines on 17 November 2019, using an Airbus 320 aircraft. (Source: Flight Aware.)



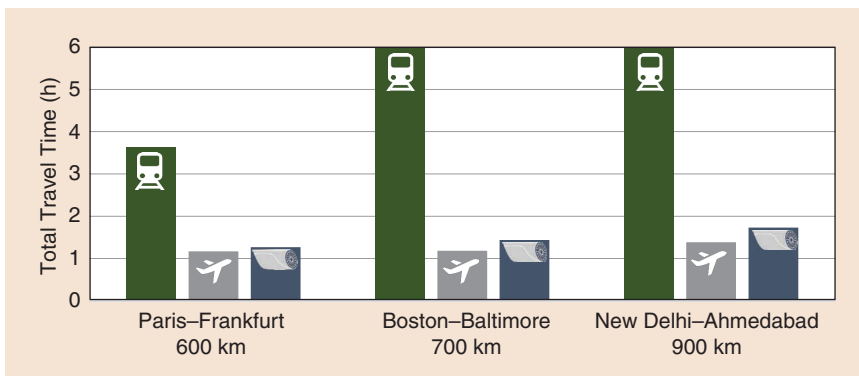
**Figure 5.** A daily flight from Delhi to Ahmedabad, India (900 km), spends less than 70% of the time cruising.



**Figure 6.** The power required for a generic, 150-passenger, short-haul aircraft designed for a maximum range of 3,000 nautical miles and a 1,000-nautical-mile (1,800-km) mission.



**Figure 7.** The operating pressures for different vehicles. (Sources: SR-71 Online and Red Bull.)



**Figure 8.** Point-to-point times for different transport modes. (Sources: SNFC, Deutsche Bahn, Indian Railways, Amtrak, and Flight Aware.)

Depending on the size of a hyperloop's cargo and passenger cabin, the mass air flow that the electric turbofan takes in may have to be compressed beyond the desired pressure ratio for propulsion efficiency. For such cases, regeneration through an air turbine is required to achieve high-efficiency values. Hyperloop vehicles must have very high overall efficiency, otherwise, energy that is not used for propulsion will be introduced into the track environment, altering the optimum operating conditions. From a

safety and reliability point of view, higher pressures facilitate these systems with confidence at 10 kPa. The Concorde proved that pressurized cabins and turbofan engines could operate at pressures lower than 10 kPa (Figure 7). The technology for operating at those pressures has a high level of maturity, which guarantees its use for passenger and cargo transportation. Below these pressures, the inefficiencies of turbomachinery are well studied, and a method to avoid the piston effect is required.

From a turbomachinery and pressurized cabin point of view, the Concorde's roof could be established for passenger and cargo transportation as a certified limit. In terms of safety, a boundary could be established at the Armstrong limit of 6.26 kPa. Operating at vacuum levels lower than the Armstrong limit is potentially beneficial for energy consumption, given the almost complete mitigation of adverse aerodynamic effects. However, cabins certified to operate at those pressures have specific and restrictive safety protocols that may be unfeasible for massive passenger transportation systems. Currently, vehicles operating below the Armstrong limit cannot ensure survivability in the event of depressurization, making this approach riskier. Typically, the threat is mitigated using space suits, such as those for high-altitude flights, that provide military pilots and astronauts a unipersonal breathing environment.

All hyperloop systems will benefit from progress in electrical technology to offer a zero-direct-emission system. They will be designed from their foundations to provide green

transportation. They will not only be fossil fuel free but also quiet, since most or all noise produced will be kept inside the tube. Solar panels and windmills will be the preferred source of energy whenever possible.

### Main Operational Characteristics of the Proposed Hyperloop System

It has been proved through simulation that hyperloop vehicles can be built to accommodate up to 200 passengers, so they are being designed to carry between 50 and 200 people. The largest and most common regional airplanes, the Airbus A320 and Boeing 737, can carry up to 185 passengers. Thus, the system is aligned with true market needs in this respect. Also, for the proposed range and design, the more passengers a vehicle carries, the more efficient it becomes in terms of consumption per seat. Nonetheless, vehicle capacity can be adjusted to specific needs, accommodating 50, 75, 100, or 130 riders. Most likely, the first to be deployed will carry 50 passengers, enabling power requirements to be more easily met and providing enough capacity for most of the potential corridors. Considering a single tube per direction and 16 h of daily operation, and a tentative minimum headway at a cruise speed of around 5 km/h, 38,400 passengers per day per direction could be accommodated, with a flow of 2,400 passengers during peak hours. For a point-to-point network targeting distances longer than 500 km, these figures are sufficient in most cases, and there is still a reasonable margin for improvement.

Furthermore, one key benefit of the proposed system is that it could complement air traffic. It has the potential to add highly required capacity in already congested corridors. Also, a dynamic simulator was developed to estimate the cost in time and energy that Zeleros's concept requires. The results are compared with planes and trains for different routes on three continents (Europe, North America, and Asia). Each is representative of distances ranging from 600 to 900 km. In Figure 3, it can be seen that the energy consumption is far closer to that of trains, being more than two times less than that of planes. In Figure 8, the travel time matches planes at a cruise speed of 650 km/h and is far better than any rail service covering the same distance.

### Current State of Development and Next Steps

Several private companies are involved in hyperloops: Zeleros; Hardt, in The Netherlands; Nevomo, in Poland; Transpod, in Canda; and Virgin Hyperloop and Hyperloop Transportation Technologies, in the United States. Thanks to rapid growth and maglev initiatives in Asia, almost all of the hyperloop system has been tested on a laboratory scale. The larger development has been done by Virgin Hyperloop. In its 500-m tube, a capsule reached 387 km/h in 2017, using magnetic propulsion and passive maglev in a low-pressure environment. Later, in 2020, a similar capsule transported two people up to 173 km/h.

Although almost all the technologies have been tested, major challenges remain in how to integrate them in an

efficient and commercially operable vehicle. The behavior of the magnetic system at 1,000 km/h (for levitation and propulsion) is an uncertainty, as the fastest maglev speed to date is 603 km/h, reached on the Japanese Shinkansen in 2015. Other issues such as cabin conditioning, emergency evacuation protocols, and vehicle flow at stations are unresolved. Apart from technology development, there has been a huge step forward in terms of certification. In the European Commission, a standardization committee has been created, and the requirements for this means of transportation are being developed.

### Acknowledgment

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