Hyperloop as an innovative new mobility mode: Squaring the circle in high-speed transportation systems?

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Abstract.
The Hyperloop innovation is a carbon-free high-speed concept for mid/long-distance connections as a complement to the railway network both in preserving investments already completed and planned and in unlocking the full economic and social potential of areas not yet adequately served. A low-pressure tube system results in substantially reduced air friction, thus allowing speeds to increase while significantly lowering energy consumption in comparison to conventional modes of transport. Hyperloop has a similar network topology as highways, enabling direct connections between origins and destinations without intermediate stops. Hyperloop has a small infrastructure footprint while enabling for a high transport capacity at minimal energy usage. Flagship 7 of the EU's Sustainable and Smart Mobility Strategy – Innovation, Data and Artificial Intelligence for Smarter Mobility - identifies Hyperloop as one of the game changing mobility technologies. The European Commission is working on a regulatory framework (Q1 2024) covering health, safety, security and environmental standards for the construction and operation of Hyperloop systems with autonomous levitating pods carrying passengers or goods at high speed inside low-pressure tubes.

Keywords: Hyperloop, climate impact, transportation, mobility

1 Introduction

Transportation is heavily challenged by global phenomena such as population growth, urbanization and climate change leading to contrasting needs of providing more frequent and faster connections while reducing the impact on the environment. A substantial share of the high standard of living in the modern world is attributable to the availability of excellent transport infrastructure. It grants access to goods, services, employment, recreation and interconnection. While the transport sector fulfils a pivotal socio-economic role, the sector is simultaneously one of the largest energy consumers, responsible for about 25% of the global CO_2 emissions [1]. Unless immediate measures are taken, global transport emissions are proposed to grow by 60% by 2050 [2], causing the international community to fall dramatically short of the Paris Agreement's goal of limiting global warming to well below 2°C as well as the recent goal of Europe to become a CO_2 neutral continent by 2050. Therefore, the transport sector has a large responsibility in implementing clean transportation alternatives to combat climate change.

The emission reductions and energy savings must be very significant. This is why new paths should be explored with approaches different to the incremental improvements made in traditional transportation today. An energy reduction of more than 90% with today's transport modalities is not possible as a matter of fact. Air resistance – governing predominantly the energy loss in high-speed transportation - cannot be avoided for any future vehicle iterations. Hyperloop and CargoTube propose a guided vehicle in low-pressure tubes at 1% to 1‰ of atmospheric pressure, drastically reducing drag and avoiding much of the energy use otherwise wasted in high-speed transportation.

Hyperloop strives for a radical new paradigm and technology on high-speed transportation which will be developed within a Pan-European context from the very beginning, therefore bypassing the traditional problems of technologies derived of national developments such as the non-yet interoperable European railways systems. The innovation setup in terms of high-speed infrastructure relies on having a European wide system without interoperability barriers, very focused in the business cases point to point, with a European dimension and therefore without the traditional national-devoted vision of the High-Speed Rail (HSR).

2 Hyperloop concept

The old vision of a vacuum tube transportation (VTT) system, combined with contemporary technologies, has recently successfully attracted great interest worldwide and represents a modern and alternative means of ground-based high-speed and sustainable transportation to counteract the ever-increasing global CO_2 emissions.

The system consists of tubes above or underground containing a partially evacuated, low-pressure environment to minimize air resistance through which a vehicle travels at up to the speed of an aircraft and even lower energy consumption compared to current HSR. A vehicle travels by means of magnetic levitation to achieve a low-friction suspension with minimal maintenance and is accelerated e.g. through an external linear motor propulsion system. Its expected high transport capacity, tiny infrastructure footprint and the unique possibility to connect cities along a line without disrupting long-distance travelers, make the Hyperloop an exceptional solution. Furthermore, Hyperloop will be independent of outside factors like weather for example. This makes Hyperloop an alternative to rail and aviation that people will be more likely to use, as reliability and speed increase while the carbon footprint decreases.

The general structure of Hyperloop includes: a superstructure (two parallel tubes), a substructure (columns elevated infrastructure (cf. Fig. 1), segmentation doors, environmental control (pump stations to maintain low-pressure environment), emergency and contingency exits, a tractive system (specifically for acceleration and cruising segments) and a power infrastructure. Hyperloop has a small infrastructure footprint while enabling for a high transport capacity at minimal energy usage.

Fig. 1. Part of the northern loop of the TVE's maglev guideway at Lathen, Germany. Continuous loop layout, 32km length. Inset: Elevated Hyperloop bi-tube design [3]

The Hyperloop concept for mid/long-distance connections serves as a complement to the railway network both in preserving investments already completed and planned and in unlocking the full economic and social potential of areas not yet adequately served. The network topology is like highways, enabling direct connections between origins and destinations without intermediate stops. In the network, vehicles can enter and exit the mainline through on and off ramps without slowing down or interrupting the flow of traffic.

3 The nub of the matter - aerodynamics

Any object moving at a given speed through a fluid or compressible medium like air experiences a force, the so-called drag force, acting opposite with respect to the relative motion. While being linearly depending on the velocity at low speed, the drag force is proportional to velocity squared at high speed. The Reynolds number (Re) associated to the flow and characterizing laminar or turbulent flow distinguishes between low and high, i.e. at ca. $Re > 1000$. Aerodynamic losses scale with the velocity cubed due to aero- and thermodynamics and cannot be recuperated by any means like all friction-based losses. In HSR transportation at 250 km/h and above these losses account up to more than 83% of power used to push even a streamlined train through air at atmospheric pressure [4].

Hyperloop is a very specific case of aerodynamics since the vehicle travels in an unconventional flow regime at rather low Reynolds numbers but at high Mach numbers surplus restricted to the confined environment of the vacuum tube, thus potentially leading to supersonic effects like choking the gas flow at the Kantrowitz limit. Thus, designing the pod’s geometry, size, and tube dimensions is crucial to be able to take full advantage of the Hyperloop approach, which needs to be avoided by the system design. (cf. e.g. [5,6] and bibliography within).

Even within the evacuated tube, the dynamics of the remaining air sets the boundaries of this technology. The flow dynamics in the narrowed gap between a pod and tube wall limit key design parameters such as diameter and target speed of a pod. Exceeding a certain threshold will nullify the benefits of this concept. Due to the constrained space, the only option to increase room for payload is to increase the pods length. This approach, however, introduces new fluid dynamical challenges such as the development of a viscous layer which effectively increases the pods diameter. Depending on the considered pod length, the results of laminar and turbulent boundary layer model vary substantially [7].

Oh at al. performed a thorough modelling and simulation of an exemplary comparison between traveling at ambient air pressure (1013 mbar) and within an evacuated tube (1 mbar) to evaluate the power savings. Assuming a travel duration of 15min covering a distance of ca. 315 km at a speed of 1260 km/h the drag force was reduced by a factor of 371 resulting consequently in a power drop from 35,661 kW to 96 kW. Experiments conducted at the Korea Railroad Research Institute showed, that other external costs like initial evacuation of the tube and maintaining the pressure at 1mbar can be neglected in case of a steel tube with low leakage rates. This also includes the CAPEX costs of the vacuum pump equipment required [8].

4 Infrastructure and Network

Network simulations and transport models indicate a modal shift, with people choosing Hyperloop over cars and flights, leading to a reduction in short-haul flights and congestion. The energy-efficient design of Hyperloop and the resulting shift contributes to lower energy consumption and positive climate impacts by reducing emissions and addressing environmental concerns. Improved connectivity between regions drives economic growth and facilitates movement of goods and people. Significantly reduced travel times enable expansion of daily urban systems, granting individuals freedom to live and work in a wider range of locations, promoting flexibility and creating economic opportunities. Moreover, existing high-speed rail networks can benefit from integration with Hyperloop, increasing their ridership and improve overall transportation efficiency. Potential routes are evaluated to be added to a more sustainable TENT-T network of the future.

Hyperloop requires a strip of land only 8 meters wide for routing, compared to higher values for high-speed trains and even greater values for highways (cf. Fig.3). Moreover, because the Hyperloop's noise emissions are virtually zero and there are no other harmful emissions, it can be connected much closer to urban infrastructure. This makes integration much easier than with existing solutions such as rail, road and subway, which are difficult to expand due to their space requirements, land acquisition and noise emissions. [9]

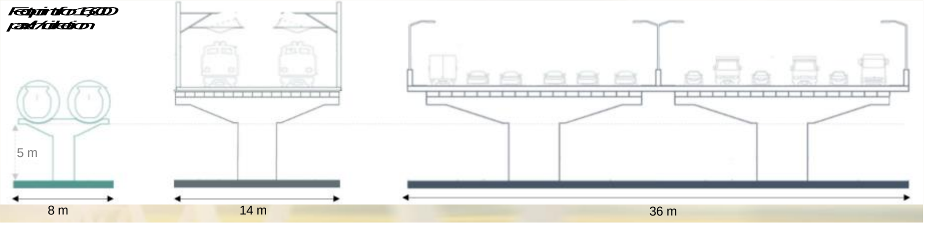

Fig. 2. Land use with comparable passenger volumes for road, rail, and Hyperloop transportation systems [9]

Flagship 7 of the EU’s Sustainable and Smart Mobility Strategy – Innovation, Data and Artificial Intelligence for Smarter Mobility - identifies Hyperloop as one of the game changing mobility technologies. The International Hyperloop Association, based in Brussels, was founded in 2023 and testing infrastructure is planned at several European locations. The European Commission is working on a regulatory framework (Q1 2024) covering health, safety, security and environmental standards for the construction and operation of Hyperloop systems with autonomous levitating pods carrying passengers or goods at high speed inside low-pressure tubes [10].

5 Conclusion

As transport infrastructure plays a substantial role in the high standard of living of modern societies, technological progress in vehicles, in infrastructures and in Information and Communication Technology (ICT) solutions have facilitated the globalization of the world economy, reduced trip times and provided more comfort at a cheaper price. In high-speed transportation, drag forces induce by far the largest energy losses, scaling with the velocity cubed due to aerodynamics. Basic physics rules out the possibility that this energy can be recovered in any way. Essentially minimizing the high energy consumption due to air friction is thus the key parameter for the sustainability of future transport modes. The vision for 2050 is a zero-emission Hyperloop transport network seamlessly integrated with other environmentally friendly transport modes [11,12].

Hyperloop could provide revolutionary benefits. The relatively low energy usage predicted, together with a dedication for using green power sources, puts Hyperloop in a strong position in relation to other modes of transportation. Simulations show that a Hyperloop system is likely to be less energy demanding than HSR and air transport, due to less friction with the track, low air resistance and electrical propulsion.

However, it has become apparent that the contemporary transportation system also has severe drawbacks related to increased air pollution, noise nuisance and traffic congestion that can deteriorate the quality of life they are meant to support instead [1,2]. All of these drawbacks are overcome by a Hyperloop transportation system facilitating an intermodal new mode of transportation.

A return on investment is estimated to be achieved much earlier than for high-speed rail, as operating costs can be kept to a minimum through significantly lower operational energy requirements and maintenance needs of hyperloop solutions. Another big improvement with regard to CAPEX spending is the minimal land use and lower superstructure cost of an elevated Hyperloop system, compared to e.g. high-speed rail [9].

In a nutshell: Hyperloop is a unique approach that literally squares the circle in sustainable high-speed transport without emissions!

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