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Hyper-Speed Vacuum Transport (*Hyperloop*)

3D image of a high-speed vehicle travelling inside a tube
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Summary

- *Since Elon Musk's Concept Paper in 2013, several industrial projects for Hyperloops, pressurized capsules circulating in a vacuum tube, are under development. They make three promises: extremely high speed (over 1,000 kph), a smaller ecological footprint, and low cost.*
- *Progress on this new mode of transport is fast but the challenges are immense: technology, the economic model, environmental impact and regional planning.*
- *While this technology has yet to prove its worth, it should not be ignored by companies or public authorities for its stakes in terms of research, intellectual property, regulation or economic and human potential.*

Mr Cédric VILLANI, MP (National Assembly), First Vice-Chairman

In 2013 [1], Elon Musk, CEO of SpaceX and Tesla, spectacularly revived the idea, which he called "Hyperloop" [2], of pressurised capsules circulating on an air cushion in a low pressure tube at a speed close to that of sound [3]. These capsules could carry goods or passengers with a high frequency. According to his estimates, the infrastructure costs of a San Francisco-Los Angeles line would be divided by ten ($ 6 billion) compared to a high-speed rail line (HSL), and the trip could be made in 30 minutes with a ticket costing only 20 dollars.

Since 2013, route plans have been announced on five continents, at the request of local public authorities, in California, Canada, the United Arab Emirates, India, Northern and Eastern Europe and, just recently, in France.

What are the stakes of this breakthrough technology, which could generically be called Hyper-speed Vacuum Transport (HVT)? What is its degree of technological maturity? Will this change land use planning nationally or even continentally? Are the high-speed trains (TGVs), the first of which date back to 1981, now outdated [4]? Will short and medium-haul air transport remain competitive?

There is talk of "smoke and mirrors", of "mirages", or even of "deception", on the technological, economic and social levels. The technology is said not to be mature enough, its real costs exorbitant and its utility questionable.

After the National Transport Infrastructure Plan (SNIT), drawn up in 2011 following the Grenelle Environment Forum, after the Assises de la mobilité, organised in the 3rd quarter of 2017 under the responsibility of Élisabeth Borne, Minister in charge of Transport; before the foundational choices being made to prepare the draft law on mobility (LOM), planned for early 2019, and the subsequent budgetary planning of financing of transport infrastructure, it is necessary to analyse in detail the potentialities and limits of HVT.

Projects for high speed vehicles in a tube

There have been many science-fiction dreams in this area, such as those of Jules Vernes in 1860 in *Paris in The 21st Century* and in 1889 *In The 29th Century or An American Journalist's Day in 2889* [5].

HVT is part of a context that is also characterised by a large number of air-cushion or magnetic levitation train projects. While in China, the magnetic levitation Transrapide Maglev, which connects the city center to the airport of Shanghai, has been in service since 2004, this has never been the case, in France, of the Aérotrain on an air cushion designed by the engineer Bertin, abandoned in 1974 and of which there remain 20 km of concrete monorail test track near Orleans. Similarly with the TransRapid magnetic levitation trains in Germany and the Swissmetro in Switzerland. Japan is currently developing SCMaglev (Superconducting Magnetic Levitation), with the first section not expected before 2027. The maximum speed of these trains peaks at around 600 kph, with an operating speed of between 300 and 450 kph.

In this uncertain context, projects have been spectacularly revived as a result of Elon Musk's initiative. Musk has not filed a patent, but every year since 2015 has organised a competition for the best university projects; 20 universities from the American, European and Asian continents were selected for the award of the prize on July 22, 2018 (6). In 2016, Musk also created The Boring Company, a company that progresses the project of an underground HVT which would connect the main cities of the northeastern United States (including New York and Washington). Regulatory permits are in the process of being requested. But Elon Musk does not invest in any of HVT's approximately 12 industrial projects, which are developing in a climate of fierce competition and a race for investors. The three main young companies are:

- **Virgin Hyperloop One** (VH1) (7), in California, which has raised the most funds ($280 million), with the recent entry into its capital of Richard Branson and which is also supported by the SNCF;

- **Hyperloop Transportation Technologies** (HTT) (8), also in California, based on the original model of crowd-sourcing, with a community of researchers and engineers worldwide remunerated in stock options;

– and **TransPod** (9), in Canada, co-founded by Frenchman Sébastien Gendron with, in particular, a contribution of Italian capital.

The last two companies have recently undertaken, with the help of the local authorities and the State, to set up their European research center and a test track, near Toulouse and near Limoges.

Source : Transpod.

Three smaller companies are European: Hardt (Netherlands), Zeleros (Spain) and Hyper (Poland).

■ The technological challenges

The main technological building blocks needed for HVT already exist, the major challenge being how to integrate them. Very few documents have been published on the technologies, for reasons of competition and intellectual property (the Inductrack, JetGLide, and Quantum Power patents). The three main start-up interviewed, as part of a non-disclosure agreement with the Office, explained that considerable progress had been made since the Elon Musk Concept Paper, especially compared to previous generations of very expensive Maglev trains (10).

All the projects are based on similar **fundamentals**: two low pressure tubes (100 Pa) on pylons; centralised autopilot with all the capsules travelling at the same speed; windowless capsules (11) carrying 20 to 40 passengers (or several tons of goods); a frequency of one capsule every 30 to 80 seconds; turnouts with launching ramps; complex stations to allow frequent departures.

All companies are working on **magnetic levitation** and linear induction motor propulsion, but with important variations: active or passive magnetic levitation, continuous or intermittent propulsion, on-board batteries or energy on the ground, permanent magnets or not.

The biggest challenges have been or are about to be solved, according to the companies surveyed, with differing technical options:

– the dissipation of the kinetic energy of the capsules by reducing the thermal footprint (12), braking recovery and evacuation by the track, the capsule and the vacuum inside the tube;

– road routing, where economic optimisation would be carried out on a case-by-case basis between speed (the shorter the journey time, the more attractive and therefore profitable the transport will be) and cost (a straight line requires tunnels and viaducts) (13);

– normal acceleration and deceleration between 0.1 and 0.3 g, so as not to inconvenience passengers (14);

– magnetic fields which bypass the capsules to avoid exposing passengers;

– a device for stabilising the capsules, taking into account the imperfections, even minute ones, of the tube;

– disturbance problems at the approach of speed of sound (Kantrowitz limit);

– vacuum management through highly controlled sealing and optimisation of pumping systems;

– metal alloy tubes with regular expansion joints;

– pylons with earthquake protection properties;

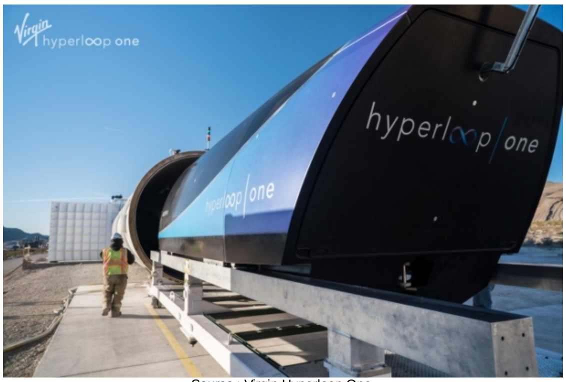
– safety devices inherited from aviation or railways, with emergency procedures in case of rapid repressurisation of the tube (airlock, evacuation of passengers ...).

■ What is a credible time horizon for deployment?

According to public information, Hyperloop Transportation Technologies is aiming for a first commissioning between Al-Ain and Abu Dhabi (United Arab Emirates) in the **early 2020s** (15). Virgin Hyperloop One, for its part, has signed a framework agreement with the State of Mahārāshtra (India) to build a line between Pune and Mumbai, which passengers could use by **the mid-2020s**. Transpod claims that it will be able to carry passengers in the early 2030s, after an initial use of its device for the transport of light goods.

The costs of HVT

Elon Musk's initial figures are being questioned. Some start-ups surveyed now estimate that the infrastructure of a HVT line would cost between 60% and 100% of that of an HSL. The geography of each route is different, with tunnels and viaducts that can lead to quadrupling construction costs. For the record, an HSL in France costs about 20 million euros per km.



Source : Virgin Hyperloop One.

But more than on the infrastructure costs (CAPEX), it is on the **operating expenses** (OPEX) that the gap would widen. The start-ups developing HVT estimate that their OPEX would be much lower than those of HSL: the absence of friction (because of vacuum and magnetic levitation) causing reduced energy consumption and mechanical fatigue; protection against bad weather (such as snow), and automation.

Today, only the Paris-Lyon HSL is financially profitable. HSLs built later have only been profitable in socio-economic terms (integrating time savings and environmental benefits). Most of the HSLs currently under development are not profitable in socio-economic terms and even less so financially. In comparison, start-ups developing HVT estimate the return on investment of their lines at between 8 and 11 years. The price of the ticket would remain lower (or equal) to that of an HSL.

The ecological stakes

As the HVT is electrically powered, it does not emit CO2 in operation, in a context where global warming is tending to increase the price per ton of CO2.

Some 70% of the energy consumption of a HSL is due to air and wheel friction: the designers of the HVT believe that the energy consumption in operation could even be lower than the production of renewable energy which would result from the installation of solar panels, or even wind turbines or geothermal units.

In comparison with the noise pollution of the plane and the train, HVT would have a very low noise level, which one of its designers estimates to be that of a plane at 50 km altitude. This makes it possible to envisage, for a line on pylons with two tubes, a corridor of a width of only 10 m.

HVT would decongest roads (reducing traffic jams and pollution) and represent a more environmentally friendly alternative to short-haul and medium-haul aircraft. It would absorb some of the world's air traffic, which has doubled every 15 years since 1945.

Social and economic stakes

Transport economists question of usefulness of speed. On the one hand, faster transport saves time, which is becoming the scarce resource of the contemporary world. It makes it possible to bring territories closer together, for example around a large metropolis, by developing economic activity, by opening up rural areas and by increasing access to work. They allow a more fluid circulation of people and ideas, an agent of progress. They free time for work but also social relations and leisure and thus improve the quality of life.

Ivan Illich, in the 1970s [16], challenged the social utility of speed, developing the notion of "generalised speed", which integrates the individual and social costs of purchasing power [17] with physical speed. These costs are first and foremost the price of the tickets. History shows that, the lower times and price per kilometre fall, the more people increase their journeys and, therefore, their time and their transportation expenses. These costs are also made up of collective costs for society: public subsidies to public transport, in a context of dwindling public funds; environmental (CO2 and noise) and energy costs; and social costs. There is a danger of creating a two-speed transport system — no pun intended — where the fastest are reserved for the richest (the Concorde was an example), with an increase in inequality.

An HSL can accommodate a maximum of 12,000 people per hour; with the new HSL (TGV) carriages, it will be possible to go up to 15,000. An HVT capsule of 40 people every 30 seconds allows a maximum flow of 4,800 passengers at peak times. Even under these best-case hypotheses, HVT **output** would still be three times lower than that of a HSL.

On the other hand, the HVT allows transport with very agile demand: no need to reserve, as soon as a capsule is full, it can leave. Culturally, it fits into the "shared economy" alongside carpooling, car sharing or even bike sharing.

HVT is a perfect match for the expected growth in e-commerce transport needs with personalized priority shipments. Operators like DHL, DP World [18] or Amazon have already shown interest. Delivery speed reduces storage costs.

Source: Hyperloop Transportation Technology.

From a land use perspective, there are many questions. Theoretically HVT would bring suburbs closer to the city centres: the advantage of better access to work or the drawback of dormitory cities? Contrary to what many local politicians believe, economists have shown that lower transport costs have favoured urban concentration [19].

While HVT seems well suited to nation-continents like the United States or India, what about small European countries already equipped with HSL? Its utility could be in the links between capitals or European metropolises, or between airports. But would the links between metropolises without intermediate stops be to the detriment of the territories being crossed?

HVT projects are not intended to replace other modes of transport, such as HSL and air links. Beyond 1,000 km, especially for journeys that necessitate crossing the sea, flying remains competitive. Although some HVT lines of less than 400 km are possible, the train has a definite advantage because of the smaller difference in duration and access to city centres that it allows without changing vehicles. This is one of the difficulties of HVT, namely that it will be very difficult, if not impossible, to build lines in major cities to the centre of town, because of the difficulty and cost of necessary expropriations. The proposed response is the connection of HVT lines to multimodal hubs - airport, metro or express subway - to seamlessly connect city centres in less than 30 minutes.

Conclusions

HVT technology has developed enormously in five years since Elon Musk concept paper. But, as we have seen, several initial objectives (notably speed and costs) have been revised.

France, a pioneer in aviation and HSL, must **ensure that it develops its public and private R & D and innovation capabilities** in this sector, whose intellectual property issues can be significant. The hypothesis of a success of this technology cannot be ruled out at this date, even if it would be prudent to wait for the technological and economic assessment of the first achievements, predicted for the early 2020s (speed, reliability, costs, security), before committing significant funding in the context of the ongoing programming of public investments in transport infrastructure, foundational for the next decades. At this stage, **this promising technology has yet to prove itself.**

The French and European **regulatory framework** would benefit from being adapted quickly to HVT. Although many technical and safety standards for rail and air transport can be implemented for HVT, significant additional work needs to be done in order to be able to certify this new mode of transport. To this end, the Public Railway Safety Establishment (EPSF) and the European Union Agency for Railways (ERA) should have their competences extended to all forms of guided transport. A group of experts could be set up, with those companies developing the HVT that so wish, with private certification bodies, or even with the European Commission, to start working right now on the regulatory characteristics relating to HVT. This approach would facilitate the risk assessment by security agencies (EPSF, ERA) and, ultimately, the European certification of this new mode of transport, if it emerges, rather than having later to import standards defined in other countries.

Finally, a **European development site** could be created, for example by redeveloping **the former Aérotrain line** near Orléans, where all players could test their products, with possible convergence or interoperability of infrastructures.

Office websites:

http://www.assemblee-nationale.fr/commissions/opecst-index.asp

http://www.senat.fr/opecst/

Experts and scientists consulted

Mr. Marcel Van de Voorde, Professor at the Technological University of Delft, the Netherlands, member of the Scientific Council of the Office

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Mr. Alexandre Cadain, CEO and co-founder of ANIMA.ai

Mr. Yves Crozet, professor at the University of Lyon (IEP), Transport Economics Planning Laboratory (LAET)

Mr. Rob Ferber, VP Chief Engineer, Ms. Diana Zhou, Director of Project Strategy and Chief of Staff, Virgin Hyperloop One

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Contributions

Academy of Technologies

Service for Science and Technology and Regional Economic Service of the Embassy of France in the United States

Endnotes

(1) Concept paper "Hyperloop Alpha": http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf.

(2) In English, "hyper-loop" means "super-loop". Since then, the name "Hyperloop" has been registered as a trademark by several companies. In this note, it is proposed to generically refer to this technology as "hyperspeed vacuum transport" (HVT), with the French acronym "THV". This last acronym is also a registered trademark in France and in Europe, for pharmaceutical and medical products (see the INPI brand database), but this does not preclude its use in another context.

(3) About 1,200 kph under normal environmental conditions.

(4) Bearing in mind that the "TGV of the future" does not forecast an increase in speed (320 kph on commercial average), but only a 30% decrease in operating costs, the use of green energy (fuel cell, hydrogen), better quality of service, autonomy and digitisation.

(5) In 1860, in Paris in the 21st Century, with a "Railway" (sic) circulating on a viaduct over the Parisian streets with a tube, compressed air and electromagnetic power, and in 1889 In The 21st Century or An American Jounalist's Day In 2889, with "aerotrains" (sic) circulating at 1,500 kph in pneumatic tubes: "If they remembered the faulty functioning of ships and railways, [...], what price would travellers not pay for aerotrains, and especially for these pneumatic tubes, spanning the oceans, in which they are transported at a speed of 1500 kph? "

(6) Hyperloop Pod Competition: http://www.spacex.com/hyperloop

(7) Virgin Hyperloop One: https://hyperloop-one.com/

(8) Hyperloop Transportation Technology: http://www.hyperloop.global/

(9) TransPod: https://transpod.com/en/

(10) Infrastructure cost approximately $100 million per kilometre.

(11) With projection of a reconstituted reality in screen windows.

(12) The best way to dissipate energy is to produce as little energy as possible.

(13) The acceptance of smaller horizontal (turning) and vertical (climbing and descending) radii of curvature would simultaneously decrease the cost of construction and the speed of movement, which would then result in an average speed of less than 1200 kph.

(14) Compatible with a passenger "standing with a coffee in their hand". Emergency scenarios provide for an emergency deceleration of 1 g, or even several g in the most extreme cases. For the record, an acceleration of 1 g corresponds to the acceleration of gravity on the surface of the earth, excluding air friction, and is 9.81 m / s2.

(15) World Expo Dubai scheduled for 2020.

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[16] Quoted by the transport economist Yves Crozet: "Appraisal methodologies and the limits to speed gains", Science Direct, World Conference on Transport Research, Shanghai, July 10-15, 2016.

[17] For him: "Today, people work a good part of the day just to earn the money they need to go to work" (Energy and Equity, Ivan Illich, 1973).

[18] In April 2018, Virgin Hyperloop One and Dubai Ports World, the world's third largest port operator, launched DP World Cargospeed, an international brand of Hyperloop optimised loading systems, to facilitate the delivery of palletised goods (https://hyperloop-one.com/dp-world-and-virgin-hyperloop-one-introduce-dp-world-cargospeed; https://www.dropbox.com/s/7e15ph4xl36prrb/3.jpg?dl=0).

[19] Hearing of Mr Yves Crozet, professor at the University of Lyon.