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ABSTRACT

The Hyperloop concept, pod speed competitions and current project developments have recently attracted much publicity. In this paper the transport technology of the vacuumed tube transport project Hyperloop is assessed through a system analysis of its principal aims, functional design, transport capacity and demand in comparison with existing commercial airlines, high-speed rail, and Maglev lines. First, the potential for high-speed long-distance travel demand for Hyperloop based on existing airline transport volumes between major airports in Germany on the one hand, and the proposed Hyperloop link from Los Angeles to San Francisco in California on the other, is assessed in general terms. Second, the technical feasibility of the proposed Hyperloop concept for vehicle design, capacity, operations, propulsion, guidance, energy supply, traffic control, safety, alignment, and construction is discussed in more detail. Third, possible environmental impacts and uncertain investment, operating and maintenance costs for implementation of a Hyperloop line are described. Finally, the risks for further Hyperloop project development and the need for more transparent research are emphasized.

1. Introduction

According to its principal protagonist, Elon Musk, Hyperloop aims to be a new mode of transport – a fifth mode after planes, trains, cars and boats – that should be safer, faster, lower cost, more convenient, immune to weather, sustainably self-powering, resistant to earthquakes, and not disruptive to those along the route (Musk 2013). It is seen as an alternative state-wide mass transit system to flying or driving at distances < 1500 km, while the planned high-speed train is considered both slower, more expensive to operate (if unsubsidized) and less safe by two orders of magnitude than flying (Musk 2013).

The Hyperloop concept, promoted in 2013 and the following design competition in 2016, as well as the student team pod competitions on a 1.6 km long, 1.83 m diameter

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partial-vacuum purpose-built steel test tube track at *SpaceX* in Hawthorne, California in 2017 and 2018 (Wikipedia 2018a), have stimulated considerable new research and development activities by students, scientists, consultants, and start-ups around the world. For example, in July 2018 and 2019, students at the Technical University Munich demonstrated that a maximum speed of 467 km/h is feasible in a partial vacuum tube with their wheel motor driven pod (240 kW, 70 kg) on the *SpaceX* test tube track and won the speed-competition for the fourth time (TU Munich 2018, 2019).

The social and political impact of the further growth of air passenger transport and combustion motor road and ship transport emissions on climate, health and fossil energy consumption intensifies public awareness and search for alternative sustainable modes of transport. The recent rapid increase in private capital investment, crowd-sourced and some public funding for Hyperloop transport research, construction of test tracks and projects for the operation of commercial lines in different countries have generated enormous expectations in the feasibility and performance of ultra-high-speed transport in vacuum tube transport technologies.

The number of accessible scientific studies is still rather limited. They focus on particular aspects of the Hyperloop, such as design and simulation of the electro-magnetic levitation force through a short-stator linear synchronous motor (Abdelrahman, Sayeed, and Youssef 2018), aerodynamic design of the vehicle (Braun, Sousa, and Pekardan 2017; Opgenoord and Caplan 2018) and simulation (Wang et al. 2017), respectively, dynamics of the tube structure and vehicle interaction (Janzen 2017), sizing models for the passenger pod (Chin et al. 2015), sizing and feasibility study for a magnetic plane concept (Decker et al. 2017), impact on bridge dynamics (Alexander and Kashani 2018) or earthquakes (Heaton 2017), as well as more general technical, operational, economic, social/environmental analyses (Van Goeverden et al. 2018; Doppelbauer 2018).

Surprisingly, none of the above studies has mentioned or reviewed the earlier Swissmetro concept developed by researchers from Ecole Polytechnique Fédérale de Lausanne/Switzerland in the period 1990–2007 (Pot and Trottet 1999; Cassat and Jufer 2002; Swissmetro 2003; Cassat and Bourquin 2011). A market and feasibility study by researchers from ETH Zurich reported in 2006 that the Swissmetro project revenues were insufficient to recover investment and maintenance costs into infrastructure and vehicles even under very optimistic assumptions (Weidmann et al. 2006). The request for granting a concession to build the Phase 1 pilot Swissmetro underground route from Geneva to Lausanne (at an estimated cost of 3.5 billion CHF (3.2 billion USD)) was not considered by the Swiss National Assembly due to missing supporting financial documents (Wikipedia 2018b). The promoting company Swissmetro AG was liquidated in 2009 having spent a million Swiss Francs of private capital (wordpress 2013).

In this paper, the essential elements of the Hyperloop system technology concept are analyzed in comparison with competing modes for high-speed long-distance passenger transport. The technical and economic feasibility of principal Hyperloop system elements and their characteristics is examined to identify the main barriers for further project development and realisation and needs for further research.
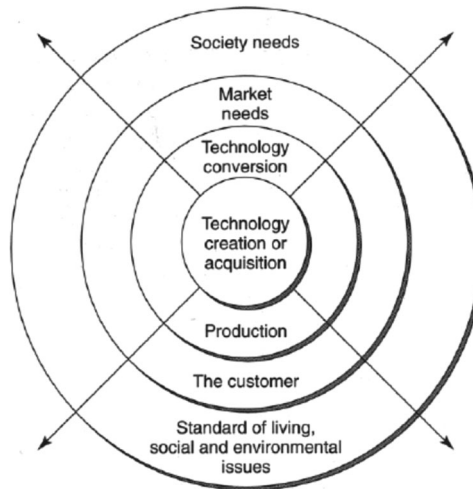
Figure 1. Spinning out technology (Source: Khalil 2000, 8).

2. Technology assessment

Managing technology is an interdisciplinary task which aims at integrating science, engineering, and management knowledge to create, acquire and exploit technology (Figure 1).

Technology assessment consists essentially of the following major steps (MITRE framework according to Martin 1994):

(1). Define the assessment task
(2). Describe relevant technologies
(3). Develop state-of-society assumptions
(4). Identify impact areas
(5). Make preliminary impact analysis
(6). Identify possible action options
(7). Complete impact analysis.

Technological progress can be achieved through inventions, research and development, when its product satisfies customer, business and societal demands. New technology can create welfare if human and natural resources as well as knowledge and capital investment contribute to economic growth and improve the standard of living and environment. However, existing societal, political, industrial and economic powers defend their roles and dominant influence, products and market, while new ideas, technological concepts and risk capital are generated by people, whose aims and interests are not satisfied.

The problem to be solved here is how to develop a technology for long-distance passenger land transport that can compete (a) on the one hand with air transport in travel time and comfort, but with less fossil energy consumption and less damage to climate

and environment, and (b) on the other hand can achieve a sufficiently high transport capacity at less investment and operating cost than high-speed railways.

Obviously, the relevant existing technologies and modes for high-speed long-distance passenger transport are aircraft, magnetic levitation and high-speed railway trains. Their future transport markets and technologies are being contested by Hyperloop promoters, developers, industrial enterprises and university student teams.

The most important technological, economic, societal and environmental questions related to high-speed passenger transport in vacuumed tubes to be answered are:

- Which operating speed, transport capacity, frequency and travel comfort is achievable by a very high-speed transport system like Hyperloop?
- Which alternative high-speed transport modes compete in the medium long-distance public transport market segment?
- Which level of market demand and supply can be reasonably expected for long distance (very) high-speed continental passenger transportion?
- Which technological barriers still exist for the implementation of new passenger transport technologies to be operated at speeds of more than 500 up to 1200 km/h in tubes like Hyperloop?
- What impacts may the introduction of Hyperloop have on land use, consumption of natural space, safety, fossil energy resources, noise emission, natural environment and climate?
- Can the prospective development, infrastructure investment, operating and maintenance cost for Hyperloop be significantly less than for aircraft, Maglev and high-speed railways and covered by potential revenues?
- Which important technical, economic and societal challenges for research and development of very high-speed passenger transport in tubes and tunnels exist?

3. System analysis

3.1. Alternative technologies for high-Speed long-distance passenger transport

Existing systems for high-speed long-distance passenger transport are commercially operated airlines and high-speed railways. Although the top speed of commercial passenger aircraft is around 900 km/h, the scheduled operating speed of airlines over distances of 400–1000 km between airports is only around 400–500 km/h due to time losses for taxiing, climbing, queuing and landing. High-speed railway trains have demonstrated maximum speeds up to 575 km/h in test runs, but the commercial operating speed of high-speed railway lines ranges between 150 and 300 km/h depending on the mean distance between stations and maximum design speed of the routes and rolling stock (Table 1). The Transrapid Maglev technology with electromagnetic support was originally developed in Germany for a design speed of 500 km/h, but reached only a maximum speed of 420 km/h on the short commercially operated 30 km airport link in Shanghai.

The electrodynamic suspension and propulsion technology of the MLX/SCMaglev has already successfully demonstrated a maximum speed record of 603 km/h on the Yamanashi test track (Central Japan Railway Company 2014; Uno 2016). The 286 km Chuo Shinkansen line from Tokyo Shinagawa to Nagoya is under construction and will start

Table 1. Technical data and estimated practical transport performance of typical aircraft, high-speed railway and magnetically levitated trains in comparison with Swissmetro and Hyperloop.

| Type	Max. speed [km/h]	Commercial speed [km/h]	Vehicle length [m]	Number of seats	Max. practical frequency	Minimum headway time [s]	Route capacity [pass./h dir.]
Aircraft	900	600	60–70	400	15/h	180	6,000
	900	400	40	200	20/h	180	4,000
High-speed train	380	250	410	1000	10/h	180	10,000
	250	150	200	450	12/h	180	5,400
Transrapid	500	225–250	125	438	12/h	300	5,250
SCMaglev	600	245		1000	10/h	180	10,000
Swiss-metro	500	323	78	200	10/h	360	2,000
				(350)			(3500)
Hyperloop	1200	1000	25	28	12/h*	300	336

*see Section 3.2.

operation in 2027. Its scheduled maximum and average speed will be 500 and 429 km/h, respectively.

The new high-speed transport technologies for operation in Hyperloop vacuum tubes would reach (almost) sonic speed. The Hyperloop passenger-only vehicle would be only 1.35 m wide, 1.1 m high, 30 m long, weigh 15 ton and offer no more than 28 single seats accessible from either side without an inside gangway (Figure 2). The prototype capsule developed by Hyperloop Transport Technologies has been presented in October 2018, is 30 m in length and has 28–40 passenger seats (Figure 3).

3.2. Hyperloop capacity

The theoretical transport capacity of a single tube Hyperloop depends on the transport capacity of the vehicles and the minimum headway time on route sections and at the terminals, respectively. The minimum headway time of Hyperloop vehicles operating in the same direction at maximum speed on vacuumed tube sections is governed by the minimum safe braking distance, which is a function of blocking time as for any
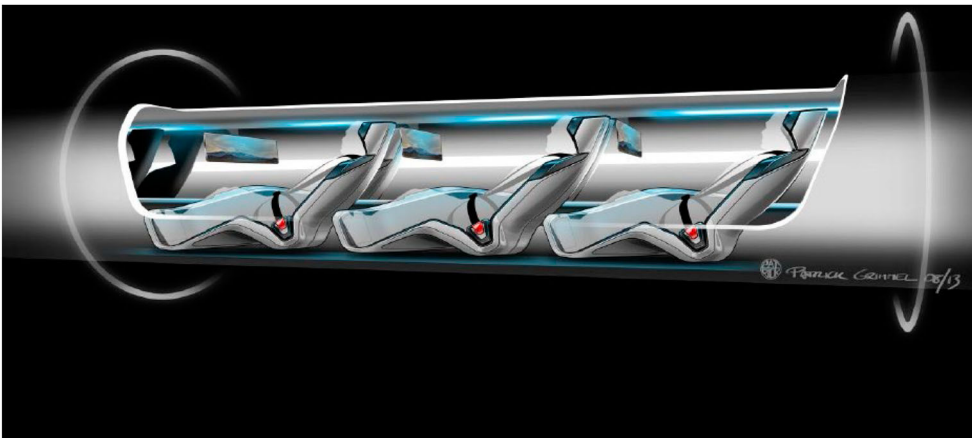

Figure 2. Original Hyperloop vehicle concept (Musk 2013).
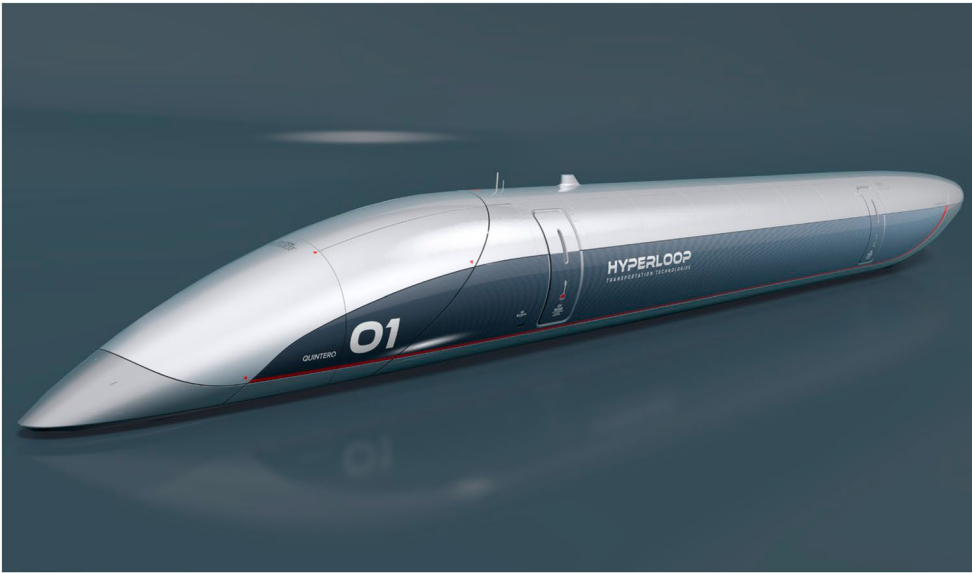
Figure 3. Hyperloop capsule body prototype (Hyperloop Transportation Technologies 2019).

track-bound system. The latter consists of the switch time for determination of the actual position, speed and acceleration of the vehicle, the movement authority (MA) given by a (communication-based) signalling and safety system (CBTC), the data processing time of the on-board operations control unit (OBU), the normal deceleration rate, and the clearing time of the concerned tube section including a safety margin.

Automatic traffic control of Hyperloop vehicles, too, would require a minimum safe headway distance similar to an ETCS level 3 moving block system that must guarantee vehicle integrity at any time and respects the minimum time for data processing and communication, the running time over their own braking distance plus a still to be determined safety margin (Figure 4) before they would arrive in front of a (fixed) signal that
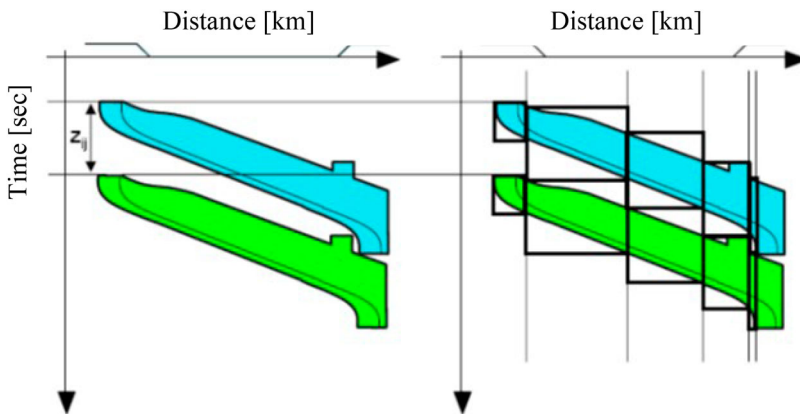
Figure 4. Blocking time bands for track-bound vehicles controlled by moving block signalling and safety systems (Source: Wendler 2006).

may transmit a MA only after a route until the first airlock has been set-up. As the inter-locking time for the route for passing two airlocks at each terminal station would last much longer than the approach time, the minimum headway time between a pair of Hyperloop vehicles following each other along the tube, the former time governs the transport system throughput (Figure 5).

Assuming a switch-time of the CBTC system including data processing time of the OBU of up to one second, which is quite optimistic and neglects latency or temporal lack of MA and OBU response in case of technical failure, the braking rate of a Hyperloop vehicle during regular operations should not exceed the standard level of travel comfort experienced by commercial airline passengers (-1.5 m/s^2), but needs to be considerably lower than the emergency safe braking rate! The latter cannot currently be determined because experimental proofs of Hyperloop pods only occurred during a few speed compe-tition runs on the *SpaceX* (partially) vacuumed small tube, while tests of full-scale Hyper-loop vehicles in wider vacuumed tubes at near sonic speed still have not been executed. A possible reference may be the standard emergency braking rate required for magnetic rail brakes of tramway vehicles up to -3.0 m/s^2, but such a high rate leading to a severe shock is not tolerable for a passenger vehicle operating at very high-speed in a vacuumed tube with no solid, continuous and high-temperature resistant linear magnetic motor.

In the case of mono-directional operation of a set of two parallel Hyperloop tubes, the operation time of twin airlocks, operation time for sequential closing, opening and vacuuming of the airlocks, moving at very low speed through the airlocks until to/ from the platform, rotation along a loop at the terminal station, dwelling at the platform gate, alighting & boarding of passengers, safety check of sealed vehicle doors, turn-around) and dispatching of vehicles would significantly increase the minimum headway time at stations to at least or more than 5 min. An indicative block time diagram for a Hyperloop line of 600 km length is shown in Figure 5.

Hyperloop vehicle operation may be limited to a simple shuttle service between two terminal stations along a pair of single vacuumed tubes that cannot be easily expanded to networks with intermediate stations or branches. These would require high-speed switches, merging/splitting of tracks and tubes, as well as double airlocks separating the vacuumed tube sections from the station and platform area (Doppelbauer 2018). The capacity of Hyperloop transport between two terminals along a single Hyperloop
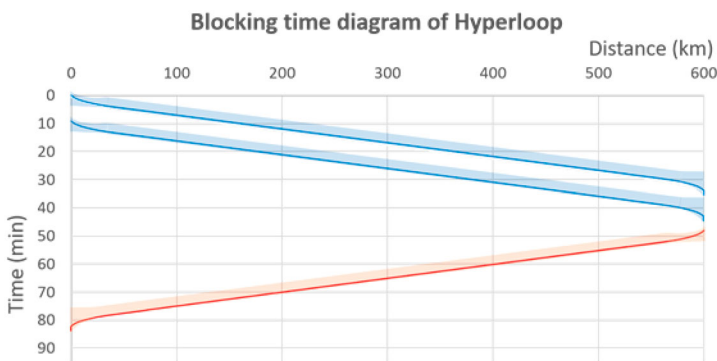

Figure 5. Blocking time and distance between Hyperloop vehicles.

tube and track in both directions would be reduced significantly due to the additional travel time between the two terminal stations.

Hyperloop vehicles travelling bi-directionally through a single tube could not depart from their platforms earlier than a vehicle travelling in the opposite direction has cleared the route through the airlocks and arrived at a separate platform section. As the block time of the final/first section at the terminals including (un)locking of vacuum resistant vehicle doors, alighting/boarding of passengers, (un)loading of baggage containers, change of battery packs, and safety check before departure will last considerably longer than the block time along intermediate tube sections, the minimum interval between two Hyperloop vehicles operated in both directions would always be much longer than the theoretical one in a single direction.

The practical transport capacity of any Hyperloop line can never be higher than the number of seats per vehicle times the maximum service frequency at its bottleneck situated at the terminal track through double airlocks. For that reason, a minimum interval of 30 s (in peak hours) and 2 min (in off-peak periods) between a pair of two Hyperloop vehicles claimed by the promoter (Musk 2013) would be infeasible. Instead, a maximum service frequency of around 12 vehicles per hour and direction is assumed for the estimation of the Hyperloop transport capacity in this study (Table 1).

Given the very small number of 28 seats proposed by Musk (2013) the practical transport capacity of a Hyperloop line would only be around 336 passengers/h and direction instead of 840 passengers/h. Also, the bigger capsule with a maximum of 40 seats developed by Hyperloop Transportation Technologies (2019) could neither achieve the desired headway time of 40 s between two departing capsules nor a capacity of 164,000 passengers/day (in both directions). The latter transport volume corresponds to 3,417 passengers/h and direction in the case of a 24 h daily operation period and approximately 20 terminal gates used simultaneously, which is incompatible with the much lower vehicle throughput of the airlocks and the required safe minimum headway distance between two Hyperloop vehicles travelling at maximum speed along the line (Section 3.5).

Thus, the considerably smaller practical transport capacity of the Hyperloop system in comparison with commercial airlines, high-speed railway trains and Maglev trains would not allow Hyperloop to compete with alternative high-speed transport modes in the same medium-distance travel market segment.

Intermediate stations with passing loops for overtaking or splitting/merging of lines between several origin and destination stations or Hyperloop terminal stations with multiple tubes, airlocks and tracks in parallel might increase the transport capacity, flexibility of vehicle scheduling and operation, but such a design seems rather utopian, as the construction of vacuum tight combined single/twin elevated Hyperloop tube sections equipped with turnouts for high-speed operation of different lines or terminal stations with multiple tracks, platforms and gates would be technically extremely complicated, require huge terminal space and considerable capital investments.

3.3. High-speed long-Distance passenger transport demand

The potential market for long-distance travellers in the U.S. for Hyperloop in the range between 500 and 1500 km may be roughly estimated based on domestic commercial air passenger transport volumes. In 2016, 720 million passengers in the U.S. (77.3% of total

commercial air passengers) were on domestic flights with an average distance of 1476 km/passenger (BTS 2018). A transport volume forecast for the Hyperloop link between Los Angeles and San Francisco/San Jose of 6 million passengers per year was reported by the promoter (Musk 2013). This volume corresponds to a maximum of approximately 15,000 passengers/day and direction depending on the divisor for the ratio between yearly and average daily transport volume (usually around 250).

The annual domestic air passenger volume, share and average distance in Germany in 2016 was only 23.7 million, 8.4% and 439 km per passenger (BMVI 2018), respectively. The current annual volume of airline transport between major German and European airports over distances of 400 km up to 1000 km is situated between 1 and 2 million passengers per direction (Eurostat 2018), which corresponds to a maximum of around 10,000 passengers/day and direction. Another estimate for the high-speed travel demand volume was a European market study, which estimated 4,000 passengers/day for the Swissmetro link between Geneva-Zurich, while 19,000 passengers/day used the railway route (Weidmann et al. 2006).

The possible modal shift from air and rail transport to Hyperloop cannot be currently quantified. This amount depends in the first instance on the frequency of transport service, real travel time reduction (including access to/from terminal stations, passenger processing, boarding/alighting times, waiting times), and the transport fare differential, and is outside the scope of this analysis.

Thus, the current volume of high-speed long-distance passenger transport of some airlines and railways on the considered corridors in California or western Europe would exceed by far the estimated practical transport capacity of Hyperloop. In particular, the small number of seats of the Hyperloop vehicle and the capacity of the basic tube line and terminal infrastructure would be insufficient to cope with more than 5% of the current air transport and high-speed railway passenger demand on major European transport links.

3.4. Hyperloop propulsion and energy demand

The propulsion of Hyperloop in the vacuumed tubes would be by external linear electric motor that provides a periodic re-boost every 70 miles (Musk 2013). An electric compressor fan mounted on the nose of the pod would actively transfer high pressure air from the front to the rear of the vessel and simultaneously create levitation, as well as air suspension when travelling at very high speed. The energy required to power the rotor on board the vehicles and the compressor of the fan is to be transmitted via a discrete magnetic linear accelerator affixed to various stations along the tube. The design and control of the proposed discrete long stator linear motor pushers in the vacuum tube, of the fan and compressor on board the vacuum sealed Hyperloop capsules still need to be developed, tested and proven experimentally.

The power for propulsion, levitation, guidance and on-board electromechanical equipment of the Hyperloop vehicles, as well as for the external compressor stations keeping the air pressure in the tubes at only 100 Pa (equal 1/1000 of the air pressure on earth) would be delivered by solar arrays mounted on top of the tubes. The promotor of Hyperloop presented no more information that supports this assertion that the energy generated by solar panels (on average 57 MW/year) would far exceed the projected total

power consumption for the Hyperloop line from Los Angeles to San Francisco (on average 21 MW and three times higher during peak demand) than additional battery power stacks at each accelerator station would store energy from the power supply grid during off-peak periods (Musk 2013).

The reported energy cost estimate for Hyperloop being less than any currently existing mode of transport (Musk 2013) is not evident and lacking any explanation. A more suitable indicator for comparing the energy consumption of different transport modes would be estimating the specific energy consumption per seat-km of high-speed trains. Unfortunately, measured real energy consumption data of commercial airlines, high-speed railway trains or Maglev trains are kept confidential by these transport companies and have not been reported in public. A second-best reference for the estimated specific energy consumption of Maglev, high-speed railway trains (ICE) and Swissmetro was reported by the promoters of Swissmetro (Cassat and Jufer 2002). However, the estimated energy data varies considerably and ranges between 46–83 Wh/passenger-km (Transrapid), 75 Wh/passenger-km (ICE), 80–180 Wh/passenger-km (Swissmetro), and 90–100 Wh/passenger-km (MLX Maglev), while Cassat and Bourquin (2011) reported even lower energy consumption values for Swissmetro.

3.5. Traffic control and safety

The claimed higher intrinsic safety of Hyperloop in comparison with airplanes and trains is not evident, because the risks of a possible failure of the extremely high emergency braking rates on the integrity of all vehicles operating and on the braking system itself have been underestimated. The integration of the propulsion system into the vacuumed tubes and the vaguely described speed supervision system cannot guarantee that the capsules can be accelerated to speeds that, according to Musk (2013), are safe in each section The elimination of risks through human control error or unpredictable weather is insufficient, unless safe headway distances, speed and acceleration supervision are continuously assured by an automatic vehicle operations control system with the same functionality as for existing automatic train operation (ATO) systems (Yin et al. 2017) like communications-based train control (Siemens Trainguard MT, Seltrac Thales CBTC] on modern driverless metro trains (e.g. in Lille, Paris, London, Singapore).

The recent claim of Hyperloop Transport Technologies and other companies to offer the safest form of transportation on the planet seems premature unless it will have demonstrated successfully a sufficient number of test runs at maximum speed to prove the required safety integrity level SIL4 and acceptable levels of passenger travel comfort. The very short minimum headway time of 30 s between Hyperloop vehicles operated at very high speed, assumed maximum acceleration of 1g, and 0.5g for braking up to 1g for emergency deceleration, respectively (Musk 2013; Decker et al. 2017) will not guarantee fail-safe operation according to proven standards of high-speed railway ATP and ATO safety systems.

Even the proposed service deceleration rate of 0.5g may not be realized in practice, because the intended linear motor can be applied for braking only at locations spaced at large distances (70 miles), whereas it will be necessary at every position in case of incidents and the mechanical braking may fail due to overheating. In fact, there will be no alternative braking system available along the intermediate route sections between the distributed accelerators apart from mechanical braking. The missing of a redundant

braking system along the whole line will be an unacceptable risk if the first one is not working properly and can cause serious lethal accidents and damage. Thus, for safety reasons, a linear motor will need to be built at least along the whole route.

Furthermore, the extremely high deceleration rates will guarantee neither high performance of the braking system at any time, nor vehicle integrity through safe headway distance in case of, for example, a combination or sequence of sudden technical failures (like power outage, lack of radio-based communication, rise of air pressure in tubes, malfunction of linear motor or mechanical braking) or missing of essential automatic vehicle control functions (movement authority, braking curve supervision, vehicle integrity, route setup and clearance), because the proposed relative braking distances between two Hyperloop vehicles are not fail-safe (i.e. may overlap and lead to collisions).

The required minimum safe distance between two Hyperloop vehicles travelling at a top speed of 1220 km/h will be approximately 58 km instead of only 37 km proposed by Musk (2013), if a continuous service deceleration rate of 1.0 m/s^2 is achieved from top speed to rest for assuring operations safety and vehicle integrity where a preceding vehicle had stopped in the vacuum tube due to, for example, a technical failure, sudden air leakage or lack of movement authority (Figure 6).

The standard safety integrity level SIL 4 (Charlwood, Turner, and Worsell 2004) according to IEC standards 61508 and 61511 requires a minimum safety rate of 10^{-8} for electrical, electronical and software products and processes, which needs to be proven explicitly by a safety case. The proposed use of auxiliary electrical on-board motors for driving Hyperloop vehicles on small wheels to the terminal after a vehicle has been stranded in the tube (Musk 2013), will not be sufficient to enable safe passenger evacuation, because a vehicle may be stranded due to the danger of a collision with a preceding stranded vehicle, damage to the track or failure of the on-board power supply. Therefore, safety scenarios for, for example, handling the emergency evacuation of passengers from several Hyperloop vehicles stranded along a route by accessing their locations via emergency doors from outside the tubes have to be developed through risk analysis and state-of-the-art safety cases. Developers will need to demonstrate the
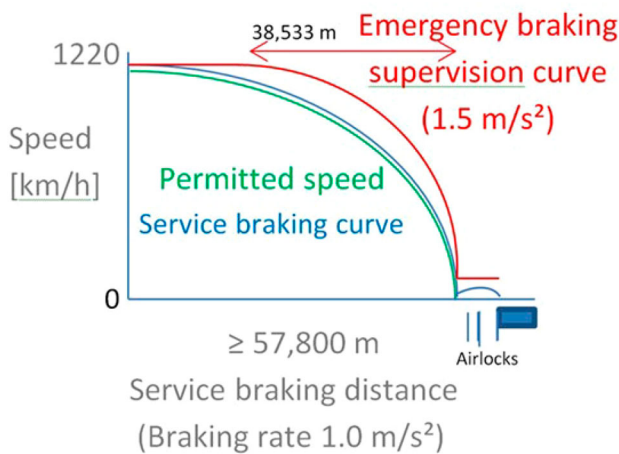
Figure 6. Absolute braking distance of Hyperloop from top speed at service braking rate of 1.0 m/s^2.

required standard safety integrity level SIL 4 for the Hyperloop transport system before for a concession to build a Hyperloop line in Europe can be awarded.

The proposed spacing of compressor stations along a Hyperloop line every 70 miles (Musk 2013) will not be sufficient to avoid a disaster in case of a major leakage in the evacuated tubes, if a continuous electromagnetic braking system was lacking in the tubes. The operation of Hyperloop vehicles may be decelerated instantaneously by dangerous jerks due to air turbulence by the sudden increase in air pressure, which may lead to a rise in temperature, mechanical contact between Hyperloop vehicle body shell and tube inner surface, damage, accidents or other calamity in a tube. Even in the case of a minor tube leakage the air pressure would rise exponentially over such a distance if the near vacuum tube sections were not separated rapidly by automatic closure of bulkheads situated at much closer distances than 100 km. Thus, more frequent vacuum pump compressor stations (say every 10 km) will be needed for potential operation of the bulkheads to create temporary airlock chamber sections and evacuation of air from accidentally ventilated tube sections after technical failures.

3.6. Guideway alignment, stations and spatial integration

The very high speed of Hyperloop will require very flat vertical radii of the tubes (30 km at 480 km/h speed and almost 200 km at 1200 km/h) and rather long ramps when gradients change, as well as very large horizontal radii for Hyperloop (approximately 7 km at a speed of 480 and 45 km/h, respectively at ideal superelevation in curves of 400 mm) to offer standard passenger travel comfort similar to conventional railways. The initially proposed minimum horizontal bends (3.7 km at 480 km/h and 23.5 km at 1220 km/h, respectively) would be too tight and lead to passenger stress by capsule and guidance magnets in curves with an intolerably high lateral acceleration of more than 2 m/s^2 even at 400 mm superelevation.

Major technological challenges confront the design and development of the platform sections, including two airlocks per tube situated close to the terminal stations, as well as the construction of durable vacuum resistant dilation joints between all tube sections. The design, development and construction of vacuum-resistant elevated twin tube sections for the split of tubes at very flat angles including very long turnouts allowing the Hyperloop capsules to branch/connect at high speed to/from different terminal stations, tracks and platforms are also major unresolved technological problems.

The airlocks for the Hyperloop tubes will segregate the first/last two tube line sections after/before the station, such that the platform areas and gates required for boarding/alighting, waiting and passenger processing will be operated at normal air pressure. When the Hyperloop vehicles approach a terminal they will enter the second last tube section, stop in front of the pressure bulkhead between the second last and last tube section (second chamber), the pressure bulkhead behind the vehicle will be shut and air from the last tube section will enter through valves until the bulkhead in front of the vehicle can be opened. Then, the Hyperloop vehicle may proceed to the last tube line segment (first chamber), which will still be segregated from the platform and station space by another pressure bulkhead. After the pressure bulkhead between the second and first chamber will have been shut, the air in the second chamber can be removed, while the air pressure of the first chamber may increase until the pressure is

equal to the terminal section and the vehicle may proceed to the platform for passenger alighting and boarding.

The departure process of the vehicle and the shutting/opening of the air chambers would simply be the reverse of this arrival process. It is obvious that the processing of passengers, vehicles and (de-)vacuuming of two air chambers is very time consuming and impacts significantly on the throughput of the terminal station. Apart from that, the design and operation of the arrival/departure junction of Hyperloop terminal stations with multiple platforms and tubes – including parking, maintenance and rotation of the vehicles – will be very complicated. This means the dispatching of Hyperloop vehicles from one terminal gateway, passing through two airlocks, control of vehicle speed, acceleration/deceleration and integrity at very high speed in vacuumed tubes, including the approach to the airlocks and gateway of the opposite terminal station, would be more time consuming than, for example, the corresponding approach times of high-speed trains and Maglev at open air stations.

A more detailed explanation as to how specially designed slip joints at stations will be able to take any tube length variance due to thermal expansion (Musk 2013) is missing. Dilation joints mounted only at stations would not be sufficient to reduce the risk of air pressure leakages due to, for example, damaged welded joints between vacuum tube segments. Additional emergency airlock chambers and hermetic entry/exit evacuation doors, as well as robust dilation joints spaced regularly at shorter distances along the route, will be necessary for safety reasons to reduce the risk of accidents and time of disruptions in case of unexpected tube leakages and the sudden rise of air pressure.

The accommodation of elevated tubes in denser settled urban areas is also a major societal problem, because of lack of space available and potential opposition by land owners, who would need to permit access for the geotechnical exploration and boring of shafts, construction of pylons, mounting of tube sections, regular inspections and maintenance. Legal procedures for granting the required rights-of-way over private and publicly owned land in the vicinity of the Hyperloop route may impact on the definitive alignment, time schedule and investment costs for the construction of the guideway. People living in the vicinity of the route may not find the visual barrier of the Hyperloop tubes and pylons acceptable and/or oppose the project because of the risk to the environment and people due to leakage, accidents or terrorist attacks. So far, such considerations have been missing from the preliminary technical design (Musk 2013).

3.7. Costs

The financial performance of the Hyperloop link from Los Angeles to San Francisco depends on four major components:

- Capital costs for financing, land acquisition, right-of-way, construction of the infrastructure and supply of vehicles,
- Operating costs for personnel (staff, traffic control, stewards, ticketing, supervision, security, training, maintenance), energy, offices, workshops, spare parts, leasing and other equipment,
- Contracting, concessions, insurance, and
- Passengers volume and fare revenues.

The capital costs for loans, land acquisition and right-of way have not been included in the preliminary technical design. These sums will be influenced considerably by the type of contract (e.g. financing exclusively by private capital or a private-public partnership supported by a certain amount of government grants). An estimation of the financing costs for a Hyperloop project at this early stage is beyond the scope of this paper.

The infrastructure construction costs depend in the first instance on the number of tubes, the total length of the Hyperloop line, the number of stations and platforms, as well as on the length of elevated and underground sections, the level above/below the ground or sea, respectively, geological characteristics of the subsurface, and finally the civil construction costs for the pylons, tunnels and tubes. A third best guess of the unit construction costs per kilometre of a single tube Hyperloop elevated guideway may be derived from the reported construction costs for the Transrapid Maglev airport line in Shanghai, which amounted to around €40 million (US$47 million) per track in 2015 (Van Goeverden et al. 2018). The projected construction costs for the proposed 93-mile Hyperloop line from Abu Dhabi to Dubai by Virgin Hyperloop One were US$4.8 billion or about US$52 million per mile (Konrad and Ohnsman 2016). The estimated infrastructure costs of the 563-km Hyperloop project from Los Angeles to San Francisco of US$ 5,410 million according to Musk (2013) corresponds to only US$10 million/km, which seems to be a significant underestimate by a factor of more than 5.

The proposed number of Hyperloop vehicles to operate on the line between Los Angeles and San Francisco of only 40 capsules – based on a travel time of 35 min at intervals of 2 min and 30 s, respectively (Musk 2013) – seems very unrealistic and infeasible (see Section 3.2 of this paper). The estimated US$54 million cost or US$1.35 million per capsule will not represent more than 1% of the total budget for this project, but in using this small number, their transport capacity will not be able to offer a higher capacity than 336 passengers/h or approximately 6,000 passengers/day and direction through a single tube.

The unit costs for a Hyperloop capsule have been recently estimated by Van Goeverden et al., (2018) at €170,000(US$202,000)/seat based on the costs/seat of the Transrapid Maglev, while the unit costs/seat derived from Musk (2013) would be only US$48,700/seat or about 3 times lower. The latter estimate for a sealed capsule resistant to extremely high acceleration, speed and near vacuum tube seems too optimistic and will be considerably higher than originally estimated by the promoter.

The total cost estimate for the construction of the Hyperloop infrastructure with double tubes and purchase of vehicles for the line from Los Angeles to San Francisco will therefore probably need to be increased by more than 500%–1000% (>US$30 to 60 billion) in order to match the expected demand of 6 million passengers/year (Musk 2013). There is also a high probability that the energy demand, consumption and costs of the Hyperloop system will be much higher than assumed. It is regrettable that a comprehensive analysis and reliable estimation of the maximum power and total energy demand of the Hyperloop system has not yet been published. Therefore, a more realistic estimation of the energy costs for exploiting a Hyperloop line like the one proposed from Los Angeles to San Francisco is not possible.

The expected amortization of the investment, operating and maintenance costs of Hyperloop including the costs of energy by the revenues of transporting 7.4 million

passengers per year in each direction between Los Angeles and San Francisco at a ticket price of only US\$20 (Musk 2013) cannot be considered as credible because of the many issues and deficiencies identified in the existing preliminary technical design from 2013.

The discontinuation of the supersonic commercial aircraft operation Concorde in 2003 (Deffrie 2018), as well as the liquidation of the promoting company Swissmetro AG in 2009 because of a lack of funding and government support (wordpress 2013) indicate the high risk for capital investment in the development of any new high-speed passenger transport technology like Hyperloop (Doppelbauer 2018).

4. Conclusions

The Hyperloop technology concept can be best compared with existing alternative modes of medium to long distance modes of high-speed passenger transport, such as conventional aircraft, Maglev and high-speed rail, as well as with the Swissmetro concept for operation of high-speed trains in partial vacuumed tunnels. Airline services offer almost the same maximum and operating speed as Hyperloop, while proven linear motor propulsion technology by Transrapid SCMaglev may be applied for Hyperloop vehicle propulsion.

The most striking difference between Hyperloop and alternative high-speed passenger transport systems is the much lower transport capacity of Hyperloop. The limited transport route capacity of Hyperloop due to the small number of seats per capsule, bi-directional operation in single tubes and strict safety constraints will probably be the most serious barrier for increasing the throughput and successful commercial operation in practice. The future transport demand for Hyperloop will depend mostly on the travel time reductions experienced in comparison with alternative modes of transport, ticket price differentials, perceived levels of travel comfort by passengers, the reliability of service and its safety record.

The possible gain in travel time over medium to long distance land transport may be affected by congestion of Hyperloop vehicles at arrival and departure stations due to the rather long process times needed for moving at low speed through the double airlocks to the platforms and the rotation of the vehicles from the arrival to the departure track. The potential travel time reduction due to the higher maximum speed of Hyperloop compared with Maglev and high-speed trains would be counterbalanced by the perceived loss of time because of queuing at check-in, security checks and gate controls similar to higher passenger volumes at major airports during peak hours. This could reduce the achievable line speed of Hyperloop in comparison with Maglev and high-speed trains.

The extremely high acceleration and deceleration rates of Hyperloop – being essential conditions to shorter travel times over medium to long distance passenger land transport – could be a substantial barrier for attracting less experienced passengers. The optimal trade-off between smoother acceleration/deceleration rates with smooth high jerks, realistic energy consumption of the whole Hyperloop transport system and competitive operating speed needs to be investigated more thoroughly.

For now, the energy consumption of Hyperloop is still unclear, because of many interdependencies between the design variables and unknown or assumed parameters used in simulation models. The reported comparison of total energy consumption per passenger-

km by Hyperloop with high-speed trains or Maglev must be considered as speculation. In the first place, it should be demonstrated experimentally: (a) the amount of solar energy that can be generated and stored through a solar array on top of a Hyperloop tube, (b) the maximum power and total energy to be demanded by compressor stations to evacuate and maintain a near vacuum air pressure in a Hyperloop tube and airlock chamber during a representative whole day and night periods of Hyperloop vehicle operation, and (c) the power and energy supply (storage capacity) needed for propulsion and braking of Hyperloop vehicles including on-board equipment by linear motors expanded over the whole length of the route, as well as charging of battery stacks to perform a total of around 1,000 roundtrips/day, while accelerating from rest to top speed of approximately 1200 km/h and decelerating at a rate of 1.0 t–2.0 m/s^2.

It may be possible that the practical operation of a Hyperloop pod in a single vacuum tube at very high-speed could be demonstrated on an (experimental) route of the type that is currently being designed or under construction (e.g. USA, France, Abu Dhabi, China). However, this would still not be sufficient to prove the feasibility and practical transport capacity of a safe and commercially viable Hyperloop transport system, because the interaction of the automatic control of speed, headway and integrity of several vehicles operating simultaneously on a line – including arrival and departure from terminals – still needs to be demonstrated.

It seems that Hyperloop promoters and developers are essentially inspired by what Latour (1996) calls their love of technology, which was identified as one important reason why the French ARAMIS people mover project failed so definitively in 1987, even at much lower speeds compared to Hyperloop. Thus, learning from the ARAMIS project would be helpful to ensure similar false impressions are avoided due to the neglect of the principles governing the safe operation, speed and headway distance control between track-bound vehicles.

Finally, finding a suitable alignment with extremely wide curves and acquisition of private land for construction of an elevated Hyperloop route in denser populated urban areas will still be a big challenge. The strong public opposition by citizens in, for example, European countries against building new infrastructure, such as new motorways, airports and railways, which may affect the natural environment, should not be underestimated. Elevated Hyperloop tubes and columns spaced every 30 m would change the landscape irrevocably, affecting local roads, bicycle or pedestrian paths and people living or visiting areas in the vicinity of a planned Hyperloop line. This problem may lead to alternative alignments with substantially longer and much more expensive underground Hyperloop sections.

The overall objective of Hyperloop to offer an ultra-fast, safer, more economic and sustainable mode of public passenger transport for medium to long-distance land transport, as well as saving (fossil) energy, protection of climate and natural environment is still very unclear, disputable and requires much more independent and transparent research.

Disclosure statement

No potential conflict of interest was reported by the author.

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