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Hyperloop – A System Engineering Analysis

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Abstract

The Hyperloop concept, pod competitions held in California and actual development plans attract recently much publicity. The idea for developing a pneumatic or guided transport system in a vacuum tube dates back more than 200 years and fascinated people due to its potential super-high speed and expected low energy demand. The technology of the most recent vacuum tube transport system Hyperloop, proposed by E. Musk (SpaceX and Tesla), is assessed regarding its principal aims, system approach and feasibility to identify the main barriers for further research, development and implementation. This system analysis is using a SIMILAR approach (INCOSE) comprising a statement of the problem, investigation of alternatives, SWOT analysis of the preliminary design of main system elements, integration, assessment of performance, and re-evaluation of the outcome. The problem is defined as how to satisfy the growing demand for passenger transport over medium to long distance (400 km up to 1500 km) in shorter time than by currently available modes of transport with less energy and impact on environment and climate. The alternative transport modes for high-speed long-distance transport considered are passenger aircraft, high-speed railway and magnetic levitation. It is shown that the proposed Hyperloop concept cannot compete successfully with existing alternative modes and technologies for medium to long distance public transport and major barriers will impede practical implementation of successful commercial operation.

Keywords: long-distance passenger transport; guideway; propulsion; high-speed; line planning, capacity; boarding & alighting; safety

1. Introduction

Since E. Musk published the Hyperloop Alpha concept for a new high-speed transport system in a vacuum tube (2013) and organized three subsequent Hyperloop pod competitions on the 1.6 km long test facility of SpaceX in California it received much publicity in the press, radio, television and internet, because 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, Not disruptive to

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those along the route" (Musk, 2013 p. 2) as alternative state-wide mass transit system to flying or driving at distances < 1500 km, because 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 p. 2). The design of the Hyperloop system has been presented as open source and feedback is desired explicitly to help advance the design and bring it from concept to reality.

Indeed, the Hyperloop concept and the following design competition in 2016, as well as the students team pod competitions on a 1.6 km long, 1.83 m diameter partial-vacuum purpose-built steel test tube of SpaceX in Hawthorne/California in 2017 and 2018 [Wikipedia, 2018] have stimulated a lot of new research and development activities by students, scientists, consultants, start-ups around the world. E.g. the students of the Technical University Munich have demonstrated in July 2018 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 1.2 km long SpaceX test track and have won again the speed-competition [TU Munich, 2018]. The social and political impact of further growth of air passenger transport and combustion motor road and ship transport exhausts on climate, health and fossil energy consumption intensifies the public awareness and search for alternative sustainable modes of transport. The recent fast increase of private capital investment, crowd-source and some public funding for Hyperloop transport research, construction of test tracks and projects for operation of commercial lines in different countries generates enormous expectations in the feasibility and performance of ultra-high-speed transport in vacuum tube transport technologies.

Three different American, British and Dutch/German consortia have raised in 2018 considerable funds for developing the Hyperloop concept to maturity. One of these consortia, Hyperloop Transportation Technologies (HTT) has already started construction of a full-scale test track (closed 320-meter facility and a 1-kilometer-long full-scale tube (diameter 4.0 m) elevated by pylons at a height of 5.8 meters) on a former military airbase near Toulouse in France [Hawkins, 2018]. Construction of the first 10 km section of the planned commercial Hyperloop line of HTT from Abu Dhabi to Dubai would start in October 2018 [Newatlas, 2018]. D. Ahlborn, CEO of the consortium Hyperloop Transportation Technologies [Wikipedia, 2018] [CNCB, 2018] confirmed a recent agreement to build 2019 a 10 km Hyperloop test track in Guizhou province/China in partnership with the Chinese Railway Corporation that would be expanded later to a full commercial line connecting the very popular touristic city of Tongren [CNBC, 2018a]. Ahlborn told also in his interview that the first full-scale Hyperloop passenger capsule is almost complete and tests will start very soon in the European research & development center of HTT near Toulouse. The prototype of the Hyperloop TT pod called QuinteroOne has been unveiled on October, 3rd 2018 in Spain and is scheduled to start commercial operation on the first line in Abu Dhabi [Webster, Oct. 4, 2018].

R. Branson's s Virgin Group is investing in the re-branded Virgin Hyperloop One $ 85 Million and Branson is joining the board [CNBC, 2017a]. The test sled of Hyperloop One coasted through the Hyperloop tube (500 m long, diameter 3.3 m) in Nevada for 5.3 seconds hitting nearly 2Gs of acceleration and a speed of 70 miles per hour during the run [CNBC, 2017b]. Branson is "talking about two to three years away, not many years away" for running of the Hyperloop One [CNBC, 2017c]. Virgin Hyperloop One and the Spanish railway infrastructure manager ADIF signed recently an agreement to invest approximately $ 500 million in an Advanced Technology Development and Testing Center in the Andalusian region of Spain [Virgin Hyperloop One, 2018]. Virgin Hyperloop One would obtain 126 million euros in public aid through loans and grants to help establish the new center, to advance Virgin Hyperloop One's technology development and testing, and to stimulate regional economic growth and job creation. Hyperloop One started or performed earlier feasibility studies for potential Hyperloop lines in the Netherlands, Switzerland, Moscow, Los Angeles, the UK, as well as Finland and Sweden. They found that a 300-mile hyperloop between Helsinki and Stockholm would cost about $21 billion [O'Kane, 2017]. Hyperloop One announced 10 winning submissions across five countries (Mexico, India, the United States, the United Kingdom, and Canada) in a long-running contest to find the best places to build the first Hyperloop tracks in the world.

T. Houter, president of Hardt Global Mobility [Hardt Hyperloop, 2018], which is a start-up of a students' team of TU Delft that won the overall design competition of the Hyperloop competition in 2017, has acquired recently in total € 5 million funding for research and development of the Hyperloop from a broad consortium of several Dutch and German companies (InnoEnergy, Uniiq, Royal BAM Group, Tata Steel, Royal IHC, Dutch Railway Company NS, Royal Schiphol Group, Engie Laborelec, DB Engineering & Consulting, Continental) [Kerssies, 2018]. The Dutch state-owned technical research institute TNO and the consulting companies Buck Consulting International, Arup and VINU have submitted 2017 a report to the Ministry of Infrastructure and Environment on the feasibility of Hyperloop in The Netherlands, in which the proposals of Hardt Hyperloop and Hyperloop One, respectively, for building a Hyperloop test facility have been evaluated, and advised to the Dutch government to build a partly publicly financed full scale, 3 m diameter, test track in The Netherlands [Arup et al., 2017]. The test track could start with a relatively low budget 3 km facility that could later be extended and integrated into a longer commercially operated Hyperloop line. The initial test track should not be dedicated to one technology or company and as such enable partnership with multiple hyperloop companies aiming for a joint public-private investment, certification and standardization process.

The number of accessible scientific studies is still rather limited. They focus on aspects of the Hyperloop as mathematical analysis and cost of the electro-magnetic levitation [Abdelrahman et al., 2018], aerodynamic design of the vehicle [Braun et al., 2017] and simulation, respectively [Wang et al., 2017], 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 & Kahani, 2018] or earthquakes [Heaton, 2017], and the operational, financial, social/environmental performances [Van Goeverden et al., 2018].

Surprisingly, none of the above studies have mentioned or reviewed the earlier “Swissmetro” concept developed by researchers from Ecole Polytechnique Fédérale de Lausanne/Switzerland in the period 1990-2007 [Pot &Trottet, 1999; Cassat & Jufer, 2002; Swissmetro AG, 2003] [https://wellpreparedmind.wordpress.com/2013/07/23/all-the-hype-for-hyperloop-but-they-forgot-swissmetro/]. A feasibility study by researchers from ETH Zurich reported that the Swissmetro project revenues were insufficient to recover investment and maintenance costs into infrastructure & vehicles even under very optimistic assumptions [Weidmann et al., 2006]. The promoting company Swissmetro AG was finally liquidated in 2009 after having spent CHF 1 million private capital because of lack of funding and government support [https://swissmetro.wordpress.com/].

The problem to be solved is developing a technology for long-distance passenger land transport that can compete (a) on the one hand with air transport on travel time and comfort, but with less fossil energy consumption and less damage on climate and environment, and (b) on the other hand can achieve a sufficiently high transport capacity at less investment and operating costs than high-speed railways. In this paper, the essential elements of the Hyperloop transport concept and their interfaces are discussed based on a rigorous system analysis and technology assessment approach in comparison with competing modes for high-speed long-distance transport to identify the main barriers for implementation and needs for further research before starting with the construction and operation of commercial projects.

2. Overview of alternative modes for high-speed long-distance 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 aircrafts is around 900 km/h, the scheduled operating speed of airlines over great distances of 400 to 1000 km between airports is only around 400 to 500 km/h due to time losses for taxiing, climbing, queuing and landing. High-sped railway trains have demonstrated maximum speeds up to 575 km/h in practice, 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.

Potential other technologies for high-speed long-distance passenger land transport are obviously magnetic propulsion and levitation systems (Maglev), in particular Transrapid (Germany/China), MLX/SMAGLEV (Japan), Inductrack (USA), and Swissmetro (Switzerland). For more detailed technical characteristics of the different Maglev systems see [Cassat & Jufer, 2002]. The top speed of Transrapid technology is specified as 500 km/h, while 430 km/h is used, so far, commercially on the 30 km long airport link in Shanghai. The MLX/SMAGLEV has demonstrated a maximum speed of 603 km/h on the Yamanashi test tracks, which will be extended from Tokyo to Nagoya and start operation in 2027. The average speed on this line is scheduled to be 429 km/h. The only Maglev system designed for operation in a partial vacuum tunnel is Swissmetro, which has a design speed of 500 km/h and may be increased possibly to 700 km/h.

Table 1: Technical data and transport performance of typical aircraft, high-speed and maglev trains

Type	Max. speed [km/h]	Commercial speed [km/h]	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		5,250
SMAGLEV	600	245		1000	10/h		10,000
Swissmetro	500	323	78	200	10/h	360	2,000

The transport capacity of the alternative modes for high-speed long-distance transport varies considerably (Table 1). The number of seats of short/medium range commercial passenger aircrafts ranges from 200 to approximately 400 passengers. As the minimum headway time between landing passenger aircrafts is usually 3 minutes at good visibility and 4 to 5 minutes at instrumented flight regime, the practical airlink transport capacity varies between 4,000 and approximately 9,000 passengers/h and direction.

High-speed railway trains have a seating capacity of between 450 and 1050 passengers depending on their length (200 and 410 m, respectively), seat density and single or double deck design. High-speed trains have proven to operate safely at high-speed and minimum headways of 4 min in one direction and achieve a maximum train frequency of 10 to 12 trains/h and direction at terminal stations with 2 platforms and 4 tracks (e.g. Tokyo). The resulting route capacity of high-speed trains ranges, thus, from 5,400 to a maximum practical capacity of 12,600 passengers.

The transport capacity of Transrapid maglev trains ranges from 200 to 438 seats depending on the train length (80 m and 125 m respectively) and seat density. At a practical frequency of 12 trains/h the Transrapid can generate a route capacity of 2,400 to 5,250 passengers/h and direction. The SMAGLEV trains have a seat capacity of 1000 passengers. The terminal stations of the Chuo Shinkansen line in construction will have each 2 platforms and 4 tracks, which may enable a practical frequency of 10 trains/h corresponding to a route capacity of 10,000 passengers/h and direction. The Swisstrain would have a seat capacity of 200 (vehicle length 78 m) and operate at a maximum frequency of 10 times/h, which may lead to a route capacity of 2,000 passengers/h and direction provided that the trains could switch platform tracks at terminal stations and enable boarding & alighting of passengers within 5 minutes.

The alignment of the Swissmetro link Geneva-Zurich would need to be built almost completely underground, while the Hyperloop link in California is projected with elevated tubes along the Interstate motorway I-5 on pillars at least 6 m high. Land acquisition, costs and right-of-way for the construction, mounting and maintenance of the Hyperloop pylons and tubes in the (sub)urban Californian metropolitan areas, as well as urban environment integration (visual obstruction) would be an extraordinary challenge. The construction of dense single tunnels for Swissmetro trains 3.2 m wide through mountains in the Alpes would be possible with proven tunnel technology, but extremely expensive. Keeping a tunnel at partial vacuum seems feasible, but it may demand a lot of powerful compressor stations with long ventilation shafts.

The Swissmetro trains would be driven, lifted and guided by laterally mounted short stator synchronous linear motors. Its drive is different from the proven long stator linear motor of Transrapid and from the repellant long stator SMAGLEV in Japan. The originally proposed air bearings (like Hoover craft) and few discrete long stator linear motor pushers for the Hyperloop vehicles in vacuum are still not proven technology. The Swissmetro trains would be 3.2 m wide, 80 m to 130 m long, have 250 to 350 seats and a weight of 130 to 156 ton. The aimed maximum acceleration of the Swissmetro trains is 1.3 m/s^2, while its standard deceleration amounts to 1.4 m/s^2 (2.4 m/s^2 emergency). The proposed maximum acceleration/deceleration rates of Swissmetro trains are at the high end of existing high-speed railway trains and may satisfy standard passenger travel comfort and safety levels if the alignment, (ideal) superelevation, vertical and horizontal curves of the guideway correspond to existing railway and respectively Maglev design standards.

The operation of twin tunnels of Swissmetro would enable either (i) bi-directional shuttle traffic in single/twin tunnels between two terminals without intermediate stations or (ii) single-directional train circulation in two tunnels with(out) intermediate stations provided there are crossover or turnouts between the two tunnels in the latter case. The airlocks for Swissmetro would be established at each of 8 station gates opposite the train doors and air compressors be connected to and powered via vertical shafts situated every 15 km along the tunnels that serve also for evacuation of passengers in case of emergency.

The capacity and minimum headway time between Swissmetro trains depends on the length of the propulsion segments, the automatic train protection and safety system. At maximum speed of 500 km/h, 15 km long propulsion segments and 1.0 m/s^2 braking rate the minimum headway time of Swissmetro trains (130 m long) would be 3.1 min. As the minimum headway time at stations is estimated approximately 6 min, the practical station throughput of Swissmetro would be around 2,000 (2,500) passenger seats/h and direction, when the seat density corresponds to ICE railway trains (Transrapid Maglev). Thus, the expected practical transport capacity of Swissmetro trains operated at a frequency of 4 trains/h would be only 50% of an ICE or TGV, because of its much shorter train length.

The reported specific energy consumption per seat-km of high-speed trains, Transrapid Maglev and Swissmetro is approximately 80 Wh/passenger-km [Cassat & Jufer, 2002 Tab. VI] and may be used as a benchmark for performance comparison.

Overall, the principle technical characteristics of alternative transport modes for medium to long distance passenger transport show a number of similarities with Hyperloop concerning (i) maximum speed of commercial aircrafts, (ii) propulsion of Maglev trains, (iii) vacuumed tube guideway of "Swissmetro", (iv) automatic piloting of aircrafts, while the vehicle size and transport capacity of Hyperloop is far less than aircraft, high-speed railway trains, Maglev and Swissmetro.

3. System analysis of Hyperloop preliminary design

A more detailed analysis of important elements of the Hyperloop transport system and performance comparison with alternative modes and technologies for medium to long distance passenger transport is necessary to identify the Strengths, Weaknesses, Opportunities and Threats (SWOT). The selection of system elements is based on an evaluation of its relevance, compliance with the current state of knowledge and technology, uncertainties and risks for innovation and implementation. The importance of the selected elements is related to its potential impact on the volume of the transport market segment, modal shift, effectiveness, efficiency, safety and sustainability.

The most critical elements of the Hyperloop system are the estimation of the(i) travel demand, (ii) transport capacity and passenger travel comfort,(ii) power demand for vacuuming the tubes, propulsion and braking,(iv) guideway alignment, stations and spatial integration, (v) traffic control and safety, and (vi) costs. First, the potential demand for very high-speed long-distance travel is estimated based on air travel statistics between some major European airports, a transport market forecast for potential "Swissmetro" corridors in Europe and air travel data for the proposed Hyperloop link Los Angeles- San Francisco in California. Second, the capacity of the passenger only vehicle, tolerated acceleration of the Hyperloop pods in (near) vacuum tubes and transport performance are compared with standards for existing railway trains and Maglev systems. Third, the estimated power supply, distribution and demand for maintaining the extremely low air pressure in the Hyperloop tubes, as well as for propulsion, levitation and braking of the pods are investigated. Fourth, the technical, operational and environmental constraints for the design of the guideway alignment, terminal stations and urban accommodation of the mostly elevated guideway and stations are identified. Fifth, the safety of the intended automatic traffic control system and robustness of the disruption management measures are compared with proven standards for railways and Maglev systems. Finally, the risks for the investment, operating cost and economic estimates for Hyperloop are briefly described.

3.1 Travel demand estimation

The potential market of long distance travelers in Europe and the U.S. for Hyperloop in the range between 500 and 1500 km can be roughly estimated on the basis of the domestic commercial air passenger transport volume. Whereas 720 million (77.3% of the total commercial air passengers) were domestic flights in the U.S. with an average distance of 1476 km/passenger in 2016 [BTS, 2017], the corresponding yearly domestic air passenger volume, share and average distance in Germany was only 23.7 million, 8.4% and 439 km [BMVI, 2017]. The current yearly volume of airline transport between major German and European airports over distances of 400 km up to 1000 km is between 1 and 2 million passengers per direction[Eurostat, 2017], which corresponds to a maximum of around 10,000 passengers/day and direction (Tab. 2).

Table 2: Air passenger transport between the main airports of Germany and their main partner airports 2017 (Source: Eurostat, 2018; own estimation of average daily numbers by 2017/250)

Airport link	Great distance	Passengers on board		Commercial passenger air flights		
	[km]	2017	2017/250	2017	2017/250	Passengers/flight
FRA-HAM	411	1395408	5582	10950	43.8	147.4
FRA-Berlin	432	1956451	7826	13349	53.4	146.6
FRA-LHR	655	1495472	5982	12533	50.1	119.3
HAM-MUC	600	1738834	6955	12471	49.9	139.4
CGN-Berlin	463	1233046	4932	10758	43.0	114.6
DUS-MUC	486	1554184	6217	13127	52.5	118.4
MUC-Berlin	480	1973008	7892	14531	58.1	135.8
MUC-LHR	942	1185799	4743	10300	41.2	115.1

The potential travel demand for the Swissmetro link Geneva-Zurich was estimated in 2006 at 4,000 passengers/day, while 19,000 passengers/day used the railway route [Weidmann et al., 2018]. The transport volume forecast for the Hyperloop link Los Angeles- San Francisco/San Jose was assessed at around 6 million passengers per year [Musk, 2013], which corresponds to a maximum of approximately 15,000 passengers/day and direction. The modal shift from air and railway transport to Hyperloop cannot be quantified at this moment. This amount depends in 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., which is out of the scope of this analysis.

3.2 Transport capacity and travel comfort

The Hyperloop passenger only vehicles would be only 1.35 m wide, 1.1 m high, approx. 15 to 20 m long, weigh 15 ton and offer no more than 28 single seats accessible from either side without an inside gangway. The theoretical transport capacity of a single tube Hyperloop depends on the transport capacity of the vehicles, operating speed of the vehicles between two terminals, operation time for closing, opening and vacuuming of the airlocks, running time of the capsules through the airlock sections until/from the platform, dwell times for alighting& boarding of passengers, turnaround time for vehicle rotation, and the minimum headway time between arrival & departure of the vehicles including safety check and dispatching.

The Hyperloop vehicle operation would be limited, so far, to simple bi-directional up and down shuttle service between two terminal stations in (a pair of) single tubes. The theoretical route capacity C of each tube is then expressed either as number of vehicles or number of passengers (seats) per time period of operation considered (e.g. 18 hours/day = 1440 min or 1 hour = 60 min/h), divided by the minimum cycle time t_c (eq. 1).

$C = 1/t_c$ (eq. 1)

The cycle time t_c of the vehicles in a single tube is equal to the sum of the blocking time and travel time t in one direction plus the interlocking, dwell and turnaround times at each terminal.

$t_c = t + t_b$ (eq. 2)

The blocking time t_b of a vehicle at departure depends on the time for setting up and clearing of the route from the platform through the airlocks until the preceding vehicle has advanced sufficiently farer than the following vehicle would need to travel over its own braking distance [Pachl, 2014]. The blocking time equals the minimum headway time $t_{h\,min}$ between a pair of vehicles travelling either in the same direction or opposite direction over the same tube section (eq. 3) (Fig. 1).

$t_b = t_{h\,min}$ (eq. 3)

As the Hyperloop capsules in a single tube cannot depart from their platform earlier than a vehicle travelling in the opposite direction has cleared the route through the airlocks and arrived on a separate platform, the route capacity is governed by the travel time between the terminals and the blocking time needed for interlocking the route until the other platform track or clearing the arrival track and rotating the capsule from one to another platform .

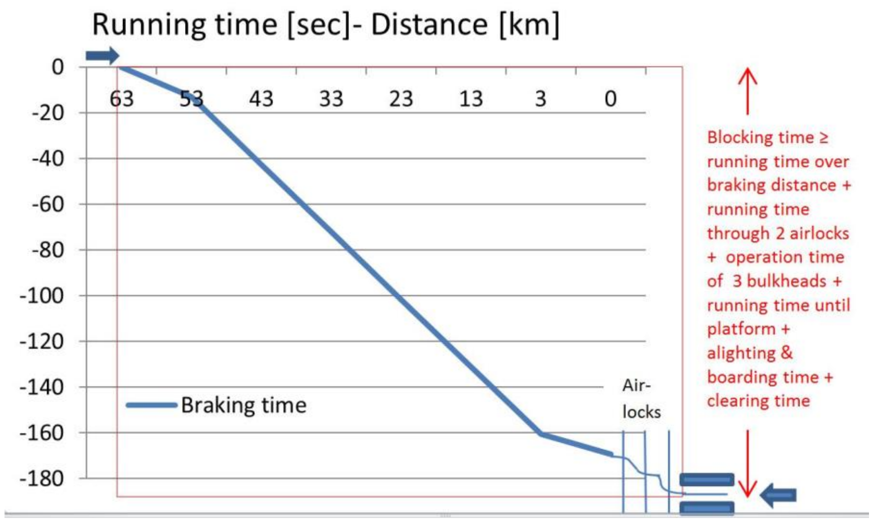

Figure 1: Blocking time between Hyperloop capsules approaching to a terminal

In case of more than one terminal track and two tubes operated each in one direction, the transport route capacity may be increased, because it depends no more on the travel time between the terminals, but only on the minimum headway time between a pair of vehicles travelling in the same direction and/or the interlocking time for setup and clearing of the route through the airlocks to platform and rotation of the vehicles via a turntable or transfer table. However, the interlocking and rotation times of the vehicles at multi-track terminals could be underestimated easily.

The practical route capacity C_p is always lower than the theoretical one due to a certain time reserve (buffer time) t_r added to the minimum cycle time (eq. 4) for recovery from delays, periodic vehicle scheduling, incidental short inspections, re-start of the automatic traffic control and operation system, and track possession for maintenance of the guideway and the electromechanical and telecommunication equipment of the tube. The typical time reserve applied on densely occupied railway lines ranges between 100% and 35% of the minimum cycle time, which reduces the theoretical transport capacity by 50% and 20% respectively.

$$C_p = 1/(t_c + t_r) \quad \text{(eq. 4)}$$

Provision of intermediate stations with passing loops for overtaking or splitting/merging of lines between different origin and destination stations would increase the flexibility and robustness of vehicle scheduling and operation even more, but the design, construction of vacuum tight combined single/twin elevated tube sections for Hyperloop equipped with turnouts for very high-speed vehicle operation of splitting/merging of lines is technically extremely complicated and remains, so far, fiction.

In fact, the Hyperloop vehicles operated bi-directionally through a single tube equipped with double airlocks between the tube and the terminals would not be able to realize neither the aimed headway time of 30 sec during peak periods, nor 2 min during other periods [Musk, 2013 p. 6], because of hard technical constraints of the required automatic traffic control and safety system. Hyperloop shuttle operation in a single tube may realize only a maximum frequency of 12 vehicles/h, provided that the blocking time of each route, platform and adjacent airlock tube section at the terminal station does not exceed 5 min and the vehicles can transfer from one arrival track and tube to another departure track at each terminal station. Thus, in practice the maximum route transport capacity of the small Hyperloop capsules could not exceed 336 passengers/h and direction.

Even in case of several tubes the throughput of Hyperloop vehicles at the critical airlock tube section in front of the terminal is limited by the rather low approach speed, safe braking rate and distance required, very complicate and time consuming opening/closing of the bulkheads and airlocks, as well as setup/clearing of routes to the platform track of the terminal station, boarding & alighting time, replacement/recharging of on-board battery packs, vacuum/air pressurization and safety check.

Thus, the practical capacity of Hyperloop would be far less than the capacity of competing long distance passenger transport systems like Swissmetro, Transrapid Maglev, Chuo Shinkansen, high-speed railway trains and commercial airlines. If Hyperloop attracted 20% of the current commercial air transport volume between Los Angeles and San Francisco, it would need to operate 54 times/h back and forth, which is infeasible due to hard infrastructure and valid standard safety constraints.

The practical capacity of Hyperloop could be increased significantly only by means of bigger, longer and consequently heavier vehicles with at least 150 seats and/or by multiplying the number of parallel tubes and use of a very complicate transfer table at the terminal stations. However, around 2.5 m wide and high Hyperloop vehicles would imply the design and construction of bigger tubes with an inner diameter of 5 to 6 m in order to keep the block ratio between the vehicle and tube cross-section lower than 0.5, which is necessary to reduce the rapidly increasing aerodynamic drag of the vehicle at higher speeds of 890 km/h [Wang et al., 2017][Chin et al. 2015]. The proposed maximum acceleration of the Hyperloop vehicles of 1g and 4.9 m/s^2 respectively in curves would be extremely high and not convenient for usual travelers. The used mean acceleration rates for the Hyperloop capsule from 0 up to a top speed of 480 km/h, 890 km/h and 1220 km/h respectively (Tab. 3) on the link Los Angeles to San Francisco, as well as the used mean braking rates have been estimated based on given incomplete data [Musk, 2013 Fig. 26/27 and Tab. 3-6]. The assumed very short acceleration times and constant acceleration rates from rest to top speed of 0.5g Musk, 2013 p. 42], as well as the extreme emergency deceleration rates simulated in the feasibility study in [Decker et al., 2017 p.6 and p.14] seem very unrealistic. The almost instantaneous jumps up and down between different speed levels presented in [Musk, 2013 Fig. 26] are very dubious and have been replaced by approximate linear gradients.

Table 3: Estimated mean acceleration and braking rates of the Hyperloop vehicles for the route from Los Angeles to San Francisco (own calculation based on indicative graphical data in Musk, 2013 Fig. 26/27)

Speed range [km/h]	0 to 480	0 to 890	0 to 1220	1220 to 0	480 to 0
Time [s]	95	268	1173	617	167
Distance [km]	22	65	365	72	56
Acceleration [m/s^2]	4.9	1.8	0.5	-0.55	-0.8

Such high average acceleration rates up to top speed would require obviously a very powerful linear motor and allow almost no (air) resistance. The maximum longitudinal acceleration from standstill would be 5 to 10 times higher than for rapid rail transit and maglev trains used in practice! A satisfactory level of passenger travel comfort in public transport could be inferred only if the starting acceleration up to 0.7 Mach was limited approximately to 2 m/s^2 and the jerk did not exceed 0.5 m/s^3. Such limited continuous acceleration and jerk rates may perhaps be acceptable for usual passengers, but would increase the travel time and reduce the operating speed of Hyperloop significantly. The aimed extremely high maximum acceleration rate of the Hyperloop pods would certainly exceed the usually tolerated level of minimum passenger comfort and impact surely on the attractiveness of the service for other than trained people.

3.3 Power demand

The power demand and distribution along the Hyperloop guideway is determined predominantly by the number and maximum power needed for evacuate the air from the tubes and for propulsion of the Hyperloop vehicles operating during peak hours. Air would leak into the evacuated tubes throughout normal operations, particularly during regular opening/closing of airlock chambers at arrival and departure of the vehicles and unintended leakages at dilation joints between tube segments because of material stress due to settlements and changes of outside air temperature. Therefore, “vacuum pumps will need to be used throughout operation to maintain operating pressure… a perfectly air tight tube is not possible” [Decker et al. 2017 p. 10 and 18 respectively]. The energy consumption of the vacuum pumps and for driving of the Hyperloop vehicles at higher speed than 500 km/h increases exponentially with the remaining air pressure level near vacuum and with growing blocking rate of the vehicle to tube space. However, as the optimal size of the Hyperloop vehicles, diameter and leakage rate of the tubes are still unknown, the estimated much lower energy consumption of the Hyperloop system in comparison with other transport modes [Musk, 2013 Fig. 1] seems to be highly speculative and overoptimistic.

Placing “solar panels on top of the tube, the Hyperloop can generate far in excess of the energy needed to operate. This takes into account storing enough energy in battery packs to operate at night and for periods of extended cloudy weather” [Musk, 2013 p. 5] is a very disputable assertion. There is no evidence that the estimated total power demand for the vacuum pump stations and for the propulsion of the Hyperloop passenger capsules of 21 MW will be sufficient. According to [Musk, 2013 p. 38/39] the estimated average power demand of 6 MW for the linear motor of the vehicle, as well as the peak power of 55 MW would be satisfied from its solar array on top the tubes.

This assertion may not hold, because the power demand of the Hyperloop requires many more compressor stations to maintain an energy-efficient near vacuum level and additional power substations to feed the linear motor for accelerating and safe braking along the line. According to the simulation results in [Decker et al., 2017 Fig. 12] the specific energy consumption of the vacuum pumps would be approximately 6 times higher than for propulsion of the pods at an optimal air pressure of 200 Pa for a leakage of 3 kg/s.

The expected 55 MW power generated by the solar power array in combination with on-board battery packs may neglect or underestimate the need to

(i) provide a continuous linear motor throughout the route (instead of only a few discrete accelerators in some tube segments) for safety reasons (see Section 3.5),
(ii) re-establish the partial vacuum in the tubes continuously through more frequently distributed and powerful compressor stations along the route particularly due to leakage in case of emergency,
(iii) higher power demand for compensation of the still unknown amount of air pressure diffusion due to frequent opening/closing of the airlock chambers close to the terminals and possible leakage of the evacuated tube segments,
(iv) provide more stand-by power stations, which can feed the compressor stations and power substations for the linear motor and maintain the near vacuum in the tubes in case of sudden leakage of the evacuated tubes, power outage, less/no output of the solar array than expected due to incidents night time and no sunshine.

The benchmark for competitive level of energy consumption is set by high-speed trains and Transrapid Maglev at approximately 80 Wh/passenger-km [Cassat & Jufer, 2002 Tab. VI].

3.4 Guideway alignment, stations and spatial integration

The very high speed levels 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 speed of 480 km/h and 45 km/h, respectively at ideal superelevation in curves of 400 mm) to offer standard passenger travel comfort for the passengers as for railways. The originally proposed minimum horizontal bend radii according to the initial Hyperloop concept (3.7 km at 480 km/h and 23.5 km at 1220 km/h, respectively) would be too small and stress the passengers, capsule and guidance magnets in curves by an intolerably high lateral acceleration of more than 2 m/s^2 even at 400 mm superelevation.

The design and development of the platform sections including two airlocks per tube situated closely to the terminal stations, as well as of the construction of durable vacuum resistant dilation joints between all tube sections for the Hyperloop are major technological challenges. Especially, 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 still a major unsolved technological problem.

The airlocks for the Hyperloop tubes would 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 would be operated at normal air pressure. When the Hyperloop vehicles approach a terminal they would 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 would be shut and air from the last tube section enters through valves until the bulkhead in front of the vehicle could be opened. Then, the Hyperloop vehicle may proceed to the last tube line segment (first chamber), which would still be segregated from the platform and station space by another pressure bulkhead. After the pressure bulkhead between the second and first chamber would have been shut, the air in the second chamber could 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 alighting and boarding.

The departure process of the vehicle and the shutting/opening of the air chambers would just be the other way round. 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 the proposed rotation of the capsule on a turntable [Musk, 2013 p. 3] would be very complicate. This means the dispatching of Hyperloop vehicles from one terminal, passing through two airlocks and supervise the traffic and integrity of the vehicles in (partial) vacuum tubes including the approach to the opposite terminal via passing through another two airlocks would last much longer than the expected time and impact on the reliability of transport services in comparison with dispatching Maglev and high-speed trains on open air guideways .

The proposed “Specially designed slip joints at stations will be able to take any tube length variance due to thermal expansion” [Musk, 2013 p. 28] have not been explained, while its provision only at stations would probably not be sufficient to eliminate the risk of damage on welded joints the individual tube segments stressed by thermal forces, which may cause dangerous leakages of the evacuated tubes. Therefore, additional robust dilation joints spaced regularly at much shorter distances along the route would be necessary to protect the tightness of joints against leakage.

The accommodation of elevated tubes in denser settled urban areas is a major societal problem, because of lack of space available and opposition by landlords, who would need to permit access for the geotechnical exploration and boring of shafts, construction of pylons, mounting of tube sections, regular inspection and maintenance. Legal procedures for granting the right-of-way of concerned private and public owned ground in the vicinity of the Hyperloop route may impact on the definitive alignment, time schedule and investment costs for construction of the guideway. People living in the vicinity of the route may not be happy with the visual barrier by the Hyperloop tubes and pylons and/or oppose to the project, because of the risk of destruction of the tubes on the environment and people due to leakage, accidents or terrorist attacks. Such concerns are missing, so far, in the preliminary technical design by [Musk, 2013].

3.4 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 could not guarantee that the capsules can be accelerated to “speeds that are safe in each section” [Musk, 2013 p. 55] is unsatisfactory. The removal of human control error and 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 (CBTC) [Siemens, Thales] on modern driverless metro trains (e.g. in Lille, Paris, London, Singapore).

The recent claim of Hyperloop TT to offer “the safest form of transportation on the planet” [Webster, 2018] 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.

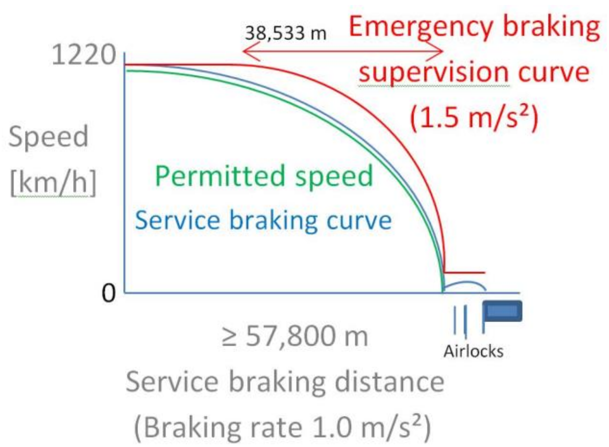

Figure 2: Absolute braking distance of Hyperloop from top speed for service braking rate of 1.0 m/s ²

The very short minimum headway time of 30 sec 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 p. 39, 42/43 Fig. 26] [Decker et al., 2017] would not permit 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 could be applied for braking only at locations spaced at large distances (70 miles), whereas it would be necessary at every position in case of incidents and the mechanical braking may fail due to overheating. In fact, there would be no alternative braking system available along the intermediate route sections between the distributed accelerators apart from mechanical braking. The absence of a second braking system would be an unacceptable risk if the first one were not working properly and could cause serious lethal accidents and damage. Thus, the linear motor would need at least to be built along the whole route for safety reasons!

Furthermore, the extremely high deceleration rates would not guarantee neither high performance of the braking system at any time, nor vehicle integrity through safe headway distance in case of e.g. 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 would be approximately 58 km (instead of only 37 km proposed by [Musk, 2013 p. 10]), when a continuous deceleration of 1.0 m/s^2 was applied from top speed to rest before a preceding vehicle that was stopped in the tube due to e.g. technical failure, sudden vacuum air leakage or lack of movement authority from a radio block center controlling the Hyperloop traffic (Fig. 2)!

The standard safety integrity level SIL 4 [Charlwood et al., 2004] according to IEC norms 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 the Hyperloop capsules by small wheels to the terminal after a vehicle was stranded in the tube [Musk, 2013 p. 55], would not be sufficient to guarantee the evacuation of the passengers, because the capsule may be stuck due to a an obstacle by a preceding stranded vehicle, damage of the track or failure of the on-board power supply. Therefore, a safety scenario for emergency evacuation of passengers from several Hyperloop capsules stranded along the route also by accessing to the spot from outside the tubes through emergency doors in the tube wall would need be considered in a comprehensive risk analysis and safety study for Hyperloop. Developers or operators of Hyperloop would be obliged to demonstrate the required level SIL 4 of the whole system, before for a concession to exploit a Hyperloop route commercially in Europe may be awarded.

The proposed spacing of compressor stations along the Hyperloop line every 70 miles [Musk, 2013 p. 4] would also not be sufficient to avoid a disaster in case of a major leakage in the evacuated tubes, because the Hyperloop pods could be decelerated instantaneously with dangerous high jerk that may reduce the air gap between pod and linear motor to zero due to sudden increase of air pressure and lead to damage of the capsule, guidance magnets and possibly linear accelerators in the tube. Even in case of minor leakage, the air pressure would rise exponentially over large distance if the near vacuum tube sections were not separated rapidly by automatically closing bulkheads at much closer distance. Thus, more frequent vacuum pump compressor stations (say every 10 km) would be needed for operation of the bulkheads to create temporary airlock sections and evacuation of the air from incidentally affected tube sections after technical failures to protect against safety risks due to leakage and allow a faster re-start of Hyperloop operation after incidents.

3.5 Costs

The financial performance of the Hyperloop link from Los Angeles to San Francisco depends on

(i) capital costs for financing, land acquisition, right-of-way, construction of the infrastructure and supply of the vehicles,

(ii) operating costs for personnel (staff, traffic control, stewards, ticketing, supervision, security, training,

maintenance), energy, offices, workshops, spare parts, leasing and other equipment, and
(iii) contracting, concessions, insurance, and on the other hand of the (iv) amount of passengers and fare revenues.

Capital costs for lending, land acquisition and right-of way have not been mentioned in the preliminary technical design. This amount will be influenced a lot from the type of contract (financing exclusively by private capital or some kind of 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 out of the scope of this paper.

The infrastructure construction costs depend in first instance on the number of tubes, the total length of the Hyperloop line, the number of stations and platforms, as well as from the length of elevated and underground sections, the level above/below the ground or sea, respectively, the geological characteristics of the soil and underground, and finally the civil construction costs for the pylons, tunnels and tubes. A third best guess of the unit construction costs per kilometer 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 per track in 2015 [Van Goeverden, 2018 p. 10]. However, the estimated infrastructure costs of the 563 km long Hyperloop project from Los Angeles to San Francisco according to [Musk, 2013 Tab. 8] correspond to only 10 million/km, which seems to be significantly underestimated by a factor 5!

The estimated number of Hyperloop vehicles to operate the line between Los Angeles and San Francisco by [Musk, 2013 Tab. 1] of only 40 capsules based on a travel time of 35 min at intervals of 2 min and 30 sec, respectively [Musk, 2013 p. 9] is very unrealistic and infeasible (see Section 3.2 of this paper). The estimated $54 million costs or €1.35 million per capsule would not represent more than 1% of the total budget for this project [Musk, 2013 p. 23], but using this small number their transport capacity would not be able to offer a higher capacity than only 336 passengers/h or approximately 6.000 passengers/day and direction through a single tube.
The unit costs for a Hyperloop capsule have been estimated recently by [Van Goeverden et al., 2018 p. 11] at €0.17 million/seat based on the costs/seat of the Transrapid Maglev, while the unit costs/seat derived from [Musk, 2013 Tab. 1] would be only $0.0487 or about 3 times lower. The latter estimate for a sealed capsule resistant to extremely high acceleration, speed and near vacuum tube seems may be too optimistic and be much higher than originally estimated by the promotor.

This means, the total cost estimate for construction of the Hyperloop infrastructure with double tubes and purchase of vehicles for the line from Los Angeles to San Francisco would probably need to be increased by more than 500% to 1000% (> $30 to 60 billion) in order to match the expected demand of 6 million passengers/year [Musk, 2013 p. 11].

There is a high probability that the energy demand, consumption and costs of the Hyperloop system would be much higher than assumed in [Musk, 2013 Fig. 1]. It is a pity that a comprehensive analysis and reliable estimation of the maximum power and total energy demand of the Hyperloop system has not been published yet. Therefore, a more realistic estimation of the energy costs for exploiting a Hyperloop line like the one 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 $20 [Musk, 2013 p. 57] cannot be considered as serious, because of the many issues and deficiencies in the existing preliminary technical design from 2013 identified.

4. Conclusions

The Hyperloop technology concept can be compared best with existing alternative modes of medium to long distance modes of high-speed passenger transport, being aircrafts, Maglev and high-speed railways, 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, whereas linear motor propulsion technology by Transrapid, Smaglev or Swissmetro may be applied for Hyperloop pod propulsion. The most striking difference between

Hyperloop and alternative high-speed passenger transport systems are the very small number of seats and the much lower transport capacity of Hyperloop. The limited transport route capacity of Hyperloop due to the small number seats per capsule, bi-directional operation in single tubes and hard safety constraints would probably be the most serious barriers for increasing the throughput and successful commercial operation in practice. The future transport demand for Hyperloop will depend mostly on the experienced travel time reduction in comparison with the alternative modes of transport, the differential ticket price, the level of travel comfort perceived by ordinary untrained passengers and the safety record.

The possible gain in travel time over medium to long distance land transport will be affected much by congestion of Hyperloop vehicles at arrival and departure due to rather long process times needed for moving at low speed through the double airlocks until the platforms and 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 will be counterbalanced by the perceived loss of time of passengers because of queuing at check-in, security check and gate control similar to higher passenger volumes at airports during peak hours. This would reduce the real travel time by Hyperloop in comparison with Maglev and high-speed trains.

The extremely high acceleration and deceleration rates of Hyperloop being essential conditions to achieve shorter travel times over medium to long distance passenger land transport could be a substantial barrier for attracting usual untrained (older) passengers. The optimal tradeoff between smoother acceleration/deceleration rates without high jerks, energy consumption and competitive travel time should be investigated more deeply.

For now, the energy consumption of Hyperloop is quite uncertain, because of the many interdependencies between the design variables and unknown or assumed parameters used in simulation models. The reported comparison of total energy consumption per passer-km by Hyperloop with high-speed trains or Maglev must be considered as speculation. It must be demonstrated experimentally first that a solar array on top of the Hyperloop tube can generate and store the maximum power and total energy demanded by (a) compressor stations to drop and maintain the near vacuum air pressure in the tube during representative whole day and night periods and (b) simultaneously feed a linear motor expanded over the whole length of the route such that the capsules perform in total around 1000 roundtrips/day, while accelerating from rest to top speed of 1200 km/h and decelerating for reasons of minimum passenger travel comfort with no more than 2.0 m/s^2.

It may be possible that practical operation of a Hyperloop pod in a single partial vacuum tube at very high-speed can be demonstrated on (experimental) routes currently designed and in construction (Abu Dhabi, China). This would still not prove the feasibility and capacity of a safe and commercially viable public transport system, because the interaction between and automatic control of speed, headway and integrity of several pods operating simultaneously on a line including arrival and departure from terminals need still to be demonstrated.

It seems that Hyperloop promotors and many developers are inspired very much by ”love of technology” [Latour, 1996], which was identified as one important reason, why the automatic traffic, speed and headway control for electronically coupled ARAMIS people movers failed in 1987 definitively even at much lower speed than Hyperloop. So , learning from the ARAMIS project would be helpful to avoid similar disillusions due to neglecting principal laws for safe operation, speed and headway distance control between track-bound vehicles.

Finally, finding a suitable alignment with extremely wide curves and acquisition of private ground for the construction of an elevated Hyperloop route in denser populated (sub) urban areas will still be a big challenge. There is a strong opposition in Europe against building new infrastructure e.g. for lines of high-voltage electrical energy transmission or new motorways, airports and railways, which may be expected also in case of Hyperloop projects connecting major airports and cities. Elevated tubes and columns spaced every 30 m would change the landscape, affect traversing local roads and paths and block the view of people living or visiting areas in the vicinity of the Hyperloop route. This may lead to the preference for substantially more and much more expensive alternative underground alignment of Hyperloop sections. The overall contribution of Hyperloop to a more sustainable public passenger transport for medium to long land transport distance, as well as to saving of (fossil) energy consumption, climate and natural environment is still unclear and needs still to be studied thoroughly by independent research.

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