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Performances of the HL (Hyperloop) transport system

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Abstract:
This paper deals with an analysis of performances of the HL (Hyperloop) transport system considered as an advanced transport alternative to the existing APT (Air Passenger Transport) and HSR (High Speed Rail) systems. The considered performances are operational, financial, social and environmental. The operational performance include capacity and quality of service provided to the system's users-passengers with attributes such as door-to-door travel time consisting of the access and egress time, schedule delay, in-vehicle time, and interchange time. The economic performances embrace the costs and revenues of operating the system. The costs include that for infrastructure, vehicles, traffic management facilities and equipment, and employees. The revenues embrace earnings from pricing users/passengers. The environmental performances include energy consumption and related emissions of GHGs (Green House Gases), and land use. The social performances are considered to be noise and safety. The analytical models of indicators of these performances are developed and applied to the scenario of operating the HL system on the short- to medium-haul travel distances/routes. These are then compared to the corresponding performances of the HSR and APT. This comparison has shown that the HL system may possess some advantages but also disadvantages regarding particular performances.

***Keywords**:* "HL (Hyperloop) system", "performances", "analysis", "modelling", "estimation".

1. Introduction

The competition between contemporary transport modes has been rather constant in the last decades. However, this does not apply for European long-distance passenger transport where the airlines increased their market share substantively. Van Goeverden et al., (2016) has estimated that air travel increased by about 45% between 2001 and 2013 while usage of the alternative modes was stable (car, train) or declining (bus). The increasing dominance of air transport has enlarged the environmental impacts of long-distance transport and this trend is expected to continue in the next decades (Lee et al., 2009; EC, 2014). The aircraft high speed in combination with comparatively low fares particularly those offered by low cost carriers has caused that requirements of travelers have become increasingly demanding, thus leading to a pressure on modes to offer high service quality particularly in terms of shorter travel times, and low fares. In addition, the environmental impact of transport has gained increasing interest, implying a growing concern with the further dominance of air transport and a demand for more environmental-friendly competitive transport alternatives. This is particularly the case since the current transport modes have been trying to adapt their commercial, environmental, and social performances, though being bounded by their technologies. For these technologies, marginal but not radical improvements have been permanently made. Radical new technologies, which could

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offer a significantly better performances, are still rare and so far have not been able to enter the transport market successfully.

The HL (Hyperloop) system is a new transport technology in conceptual stage that is claimed to provide superior performances to high speed rail and air transport, particularly regarding travel time, transport costs, energy consumption, and transport safety (Musk, 2013). At present, the existing studies on the HL technology and its experimental stage of development have not provided a real evidence for confirming or denying the above-mentioned claims including the lack of evidence about HL's performances as compared to other transport modes and their systems.

This paper aims at exploring operational, financial, and social/environmental performances of the HL system and compare them with those of APT (Air Passenger Transport) and HSR (High Speed Rail) system. The results of such comparison are intended to underpin the further discussion about the commercial, social, environmental, and also political viability of the HL system.

In addition to this introductory section, the paper consists of four other sections. Section 2 provides a brief description of the HL system. Section 3 deals with an analysis and analytical modelling of its above-mentioned performances. Section 4 gives a comparison of HL's performances with those of the above-mentioned two potentially competing transport modes - HSR and APT. The final Section (5) summarizes the main conclusions regarding the prospective advantages and disadvantages of the HL system and provides some perspectives on the market opportunities of HL.

2. The HL (Hyperloop) system

According to Musk (2013), the HL system for passenger transport is supposed to consist of capsules of the capacity of 28 seats/vehicle. It will operate in a low-pressure tube on a 0,5 to 1,3 mm layer of air featuring the pressurized air and aerodynamic lift as shown on Fig. 1. A magnetic linear accelerator positioned at the stations will accelerate the capsule with the support of rotors attached to each capsule. Passengers may board at stations at the ends of the tube or at the stations in-between. The capsules will be able to reach max speed of 1.220 km/h (max inertial acceleration 0,5g; g = 9,81m/s^2). The tubes will be based on the elevated pillars except for tunnel sections, while the solar panels above the tubes will provide the system with energy.

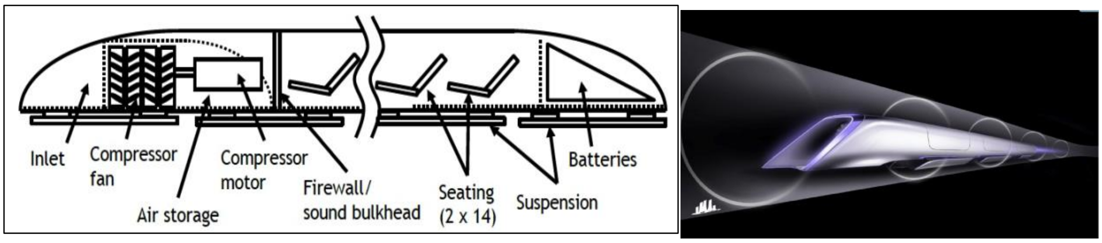

Figure 1 Conceptual design and subsystems of the HL system
(Musk, 2013)

Two variants of the HL systems are considered: a passenger only and a passenger and freight one (Musk, 2013). The latter has larger dimensions for both the capsules and the tube. The diameter of the tube is 2,23m for the passenger and 3,3m for the passenger and freight variant. The capsules of the passenger variant allow passengers only to sit since there is no room for walking through the vehicle. In addition the vehicles in both variants lack the toilets. Absence of a toilet lowers the applicability of the system because the vehicles need to stop every 30 minutes for a longer time for toilet visits. The passenger and freight capsules seem sufficiently large to enable walking through the vehicle. Their frontal area is 4,0 m^2 and the height is likely to be about 1,9

m. This paper assumes and analyses the passenger and freight variant including the toilet facilities onboard the vehicles, irrespective whether the system is exclusively used for passenger or for both passenger and freight transport.

Given its technical features, the HL is envisioned to be a transport mode for the medium- to long-distance travelling. As such, if operating along the routes without substantive physical barriers, it seems to be a good alternative to APT. At present, the HL technology is being tested in practice on the short test tracks with prototype (capsule) models.

3. Performance of the HL system

The performance of a given transport system can be considered in different ways and from the perspectives of different stakeholders involved, i.e., the users/customers, the transport operator, the governmental authorities at different institutional levels, and the society. For the users/customers the price of the transport service and its service quality (e.g., transport time, reliability, comfort) are important performance attributes; the transport operators are mostly interested in an economically viable operation. The governments may be interested in a viable operation as well (e.g., when providing subsidies), but generally have more interest in the effects and impacts of a transport system on its environment and society, like regional accessibility, noise, congestion, safety, air quality, and land use. These kinds of interest also largely represent the interests of citizens. If these different interests of stakeholders are not successfully balanced, they may block the implementation of a new transport system.

As mentioned above, aiming at facilitating these different perspectives and interests of stakeholders on transport system performance, the following performances of the HL system are elaborated: (i) operational performance; (ii) financial performance; (iii) social and environmental performance.

3.1 Operational performance

The operational performance of the HL system generally includes the system capacity and the quality of services. The former is mainly relevant for the operators, and the latter for the users/customers.

Capacity

Similarly to its counterparts, the HSR and APT, the HL system is characterized by its traffic and transport capacity. The traffic capacity is defined by the maximum number of vehicles, which can pass through the "reference location" in one direction during a given period of time under conditions of constant demand for service. In case of the HL system, this is actually the capacity of the infrastructure, i.e., vacuumed tube(s). This capacity can be estimated as follows:

$$\lambda_1 = T / \tau = \left(T \cdot a^{-} \right) / v \tag{1}$$

where

T is the period of time (h, day);

τ is the minimum time interval between two successive vehicles moving in the same direction (min);

a^{-} is maximum deceleration rate (m/s^2); and

v is the maximum vehicle's operating speed (km/h).

Equation 1 indicates that the successive vehicles moving in the same direction need to be separated at least for the maximum deceleration (breaking) distance of the following vehicle.

The transport capacity is the maximum number of passengers (and/or the volume of freight), which can be transported in one direction per unit of time under conditions of constant demand for service. This capacity is based on the product of the above-mentioned infrastructure capacity and the (equal) capacity of each vehicle, the latter in terms of the number of seats/vehicle. Based on Eq. 1 it can be estimated as follows:

$$\lambda_2 = \lambda_1 \cdot s = (T / \tau) \cdot s \cdot \theta = \left[\left(T \cdot a^{-} \right) / v \right] \cdot \theta \cdot s \qquad (2)$$

where

s is the vehicle's capacity (seats); and
θ is the vehicle load factor (<=1,0).

Multiplied by the vehicle operating speed along the line the transport capacity gives an estimate of the technical productivity of the HL system under given conditions. From Eq. 2, this maximum technical productivity is equal to:

$$TP = \lambda_2 \cdot v \qquad (3)$$

where all symbols are as in the previous Eqs.

For the practical applications, the traffic capacity in Eq. 1 needs to be replaced by the actual service frequency, generally depending on the volumes of demand and the required load factor as follows:

$$\lambda_1 \equiv f(Q) = \frac{Q}{s \cdot \theta} \qquad (4)$$

where

Q is the user/passenger demand during the specified period of time (h, day).

The other symbols are analogous to those in the previous Eqs.
In addition, the actual (scheduled) service frequency in Eq. 4 can in some cases depend on a policy regarding a 'decency' frequency.
The technical productivity in Eq. 2 can also be modified accordingly in dependence on the actual (scheduled) service frequency.

Quality of services
The quality of services influences (in addition to fares) the attractiveness of the HL services and indicates its relative advantage/disadvantage over the competing modes such as APT and HSR. Relative advantage can be seen as the degree to which an innovation is perceived better than the product it replaces or competes with (Tidd et al., 2001). Relative advantage has considered as one of the strongest predictors of the outcome of the decision on whether or not to adopt the innovation. In general, a new transport system does not need to perform better on all aspects, but overall – taking all the relevant characteristics of the service into account - it should offer some added value, i.e., benefits to its users. The following attributes of quality service of the HL system are considered as relevant in the given context.

i) Door-to-door travel time

The door-to-door travel time includes the access and egress time, schedule delay (including possible time for luggage checking) at the boarding and alighting stations, in-vehicle time, and the interchange time between different HL vehicles and their particular services at intermediate and end stations,.

The *access and egress time* depends on the interconnectivity between the HL system and the pre- and post-haulage systems, the density of the HL stations, and the speed of the pre- and post-haulage systems (from the users' doors to the HL station, and vice versa). The access and egress time generally varies at particular HL stations depending on the local spatial and traffic conditions. .

The *schedule delay* depends on the frequency of the HL services. Based on Eq. 4, it can be estimated as follows:

$$SD = \frac{1}{2} \cdot \frac{T}{f(Q)} \tag{5}$$

where all symbols are as in the previous Eqs.

The schedule delay can depend on the punctuality and connecting systems, the risk aversion of travelers for missing the intended service, and in the case of the scheduled access and egress systems, the timetables of the connecting systems.

The punctuality of the HL system correlates with the homogeneity of successive services (regarding to destination/routing, intermediate stops) and the scheduled buffer times. In the case of a network where some people have to make an interchange, the policy on whether/how long to wait for delayed connecting services can additionally affect the punctuality.

The *in-vehicle time* of the HL system depends on the travel distance, the average speed, and the stopping time at the particular stations.

If the HL system exists of a network where some travelers have to make interchanges within the system, the *interchange time* depends on the frequency of the services, the match of the timetables, the punctuality, and the policy on waiting for delayed connecting services.

The in-vehicle time and interchange time correlate with the door-to-door distance. The access/egress and waiting times are 'fixed 'times to this respect. The relative value of the latter two time components will decrease when the distance increases.

ii) Interchanges

The need to make interchanges generally diminishes the overall quality of service. Interchanges may extend travel times and make trips less convenient. In the long-distance travel markets, which the HL system is supposed to penetrate, the users/passengers usually have luggage with them. They generally will have to make at least two interchanges (between the access mode and the HL, and the HL and the egress mode). In some cases they have to make interchanges within the HL system. The opportunity of interchanges in the access and egress trips is related to the density of HL stations. The opportunity of interchanges within the HL system is related to the design of the HL network. Table 1 gives the very preliminary estimates of the above-mentioned indicators of operational performances (Taylor et al., 2016).

Table 1: Some estimates of the indicators of operational performances of the HL system and its counterparts - APT and HSR

Indicator	HL	APT[4)]	HSR[4)]
Maximum service frequency (dep/h)	10[1)]	3	12
Infrastructure capacity (veh/h)[1)]	10[1)]	-	12
Vehicle capacity (seats/veh)	28	130	1000
Transport capacity (pax/h)[2)]	224[2)]	312	9600
Technical productivity (pax-km/h)[3)]	273280[3)]	258968[5)]	3360000[6)]
Length of line (km)	600	600	600
Average operating speed (km/h)	965	407	264
In-vehicle time (minutes)	37,3	88,5	136,4
Schedule delay (min)[7)]	3	10	2,5
Total station-station travel time (min)	40,3	98,5	138,9

1) At the maximum speed of 1220 km/h and maximum deceleration rate: $a^- = 1m/s^2$; At the maximum load factor: $\theta = 0,8$; 3) At the maximum service frequency and speed, and load factor; 4) Taylor et al., 2016; 5) Average speed: v = 830 km/h; 6) Average speed: v = 350km/h; 7) Based on Eqs. 1, 4, 5

As can be seen, under given conditions, the HL system would perform better than its APT and HSR counterpart only in terms of indicators such as technical productivity and total travel time.

iii) Service frequency

Based on the technical characteristics of HL the service frequency is estimated at maximum 10 per hour, which is rather comparable to what HSR can offer.

The relevance of the service frequency as perceived by the traveller will, however, depend on the envisaged business plan of HL: either as a ‘walk up’ service (i.e. direct access without reservation in advance) or through advanced seat reservation. In a scenario with advanced seat reservation a lower frequency (i.e. 3 – 4 times per hour) would be very well acceptable, in particular in long-distance trips. On the other hand, in case of walk up services the benefits of a high service frequency can be totally frustrated when demand and supply are temporally not balanced, and hence travellers will be confronted with significant waiting times in the stations (Taylor et al., 2016).

iv) Service reliability

The HL system has two major features that enable a potential high reliability of services. HL is a completely automated system which per definition excludes delays due to human errors. In addition, HL operates in a closed environment which makes it resilient to weather conditions. Of course, like any other transport system, the reliability of the HL transport services will depend on the technical reliability of all parts of the system (i.e. capsules, infrastructure, control system).

3.2 Financial performance

The bottom line for a stable economic viability of the HL system is whether the total costs (capital, operational and overhead cost) enable a competitive price setting that attracts a sufficient number of customers. The financial performance is defined by both the costs and the revenues. This section focuses on the costs and the price that covers the cost.

Costs

The costs exist of capital costs, operational costs, and overhead costs. The capital costs are the costs for building the infrastructure (tracks, stations), and the costs for purchasing the vehicles. The operational costs regard maintenance of infrastructure and vehicles, and costs related to the operation of the vehicles and stations.

The estimation of the costs of a not existing system is a difficult job. We will produce cost figures that are based on estimations by others or, following Wilkinson (2016), on published figures regarding the actual costs of the Maglev-system; the latter is to a large extent comparable with HL.

The cost level is defined by the cost value, currency, and time. One Euro in 2010 reflects a different cost level than either 1 US Dollar in 2010 or 1 Euro in 2015. In our analysis we will come across figures regarding different currencies and time periods. In order to make the figures comparable, we will present figures that are converted to Euros of 2015.

i) Capital cost for building tracks

The capital cost for building 1 km of track is likely to depend largely on local conditions. Building in an empty area on flat sandy soil will be cheaper than building in a highly urbanized area, in moorland, or in mountains. Crossing wide rivers or the need to build tunnels will increase the costs. Musk (2013) estimates costs for two local conditions, tubes on pylons and tubes in tunnels. The estimated per-km costs of the passenger + freight variant are, converted to Euros of 2015, €10,3 million and €34,0 million.

There is one example of a high-speed Maglev connection. Between Shanghai Pudong airport and the outskirts of the city a dual track 30 km line has been built including two stations (begin and end). Published cost amounts for the whole track are $1,2 billion (Antlauf *et al*, 2004)) and $1,33 billion (Wikipedia(1)); both are US dollars in 2002. A possible explanation for the difference is the inclusion/exclusion of the two stations. Both amounts include the purchase cost of the vehicles. Excluding station costs and vehicle costs, the investment costs would have been about €41 million per km track (Euros of 2015). Cost estimates for an extension of the line to Shanghai Hongqiao Airport were just the half: about €20 million per km (Wikipedia (2)). A reported reason for the lower costs is using all-concrete modular design that would reduce the cost by 30%. A second possible reason for the lower cost is a more solid soil. The current track was built in an area with seismic activity and weak alluvial soil. This required to base the construction on piles which raised the costs. Another estimate is for a proposed Maglev line in the Melbourne area. The estimated cost per km were AU $34 million (TKTA, 2008), which equals €26 million in 2015. This estimate is somewhat higher than for the Shanghai extension. Considering that cost estimates generally are too low and therefore the Melbourne estimate might be more realistic than the Shanghai estimate, we assume that the costs of a km Maglev track are in the order of €25 million under favorable conditions.

The costs of 1 km HL track will not be equal to the maglev costs. Wilkinson (2016) argues that the HL costs are likely to be somewhat higher because the Maglev has no costs in tube construction and vacuum pumps. On the other hand, HL needs no concrete guideway unlike the Maglev. We assume that the construction costs of the two systems are in the same order of magnitude and adopt the figure of €25 million for one km HL on solid soil. This is more than double the costs that were estimated by Musk (2013).

Assuming that the actual cost of €40 million for the current Maglev track built on weak soil could have been reduced somewhat by using a modular design, the costs for building one km could be €35 million. We assume this figure for the HL system as well.

The estimated costs for building tunnels by Musk (€34,0 million per km HL) can only be compared with railway tunnels or road tunnels. The cost of the Gotthard base tunnel was about €200 million per km; this tunnel consists of two single-track tunnels (Wikipedia(3)). The estimated costs of the Chuo Shinkansen railway line in Japan between Tokyo and Nagoya are €160 million per km; 60% of the line goes through tunnels (Quora). The per-km costs of the tunnel sections are likely in the same order of magnitude as those for the Gotthard tunnel. The Channel tunnel between France and Britain costed £4,65 billion in the 1990s for 50,5 km (Wikipedia(4)). This is about €190 million per km. The conclusion is that the per-km tunnel costs for a double track railway line are in the order of €200. These are likely considerably higher than the costs for HL because the diameter of the HL tube is much smaller. The two single-track Gotthard tunnels have diameters of about 9 m, one HL tube as proposed by Musk

(2013) has a diameter of 3,3 m. The tunnel construction costs for two HL tubes might then even be somewhat lower than the cost for one single-track rail tunnel. We assume that Musk underestimates the cost by about a factor 2, just like the argued underestimation for the tube on pylons, and that the real costs for two parallel tubes would be in the order of €70 million per km.

ii) Capital cost for building stations/terminals

The building costs for a station/terminal were estimated by Musk (2013) at $125 million, which is €116 million. The costs for the two stations of the current Maglev line near Shanghai could be the difference between $1,33 and $1,2 billion, which is $130 million for two stations (€77 per station); this is significantly less than the amount mentioned by Musk. However, HL stations are more complex than Maglev stations because they should give access to vehicles in evacuated tubes. We assume that €116 million is a good estimate for the investment cost of one (basic) station. Stations at nodes of the network where several lines connect will be more expensive.

iii) Purchase costs of vehicles

The costs for purchase of a vehicle (capsule) were estimated by Musk (2013) at €1,42 million. Musk's vehicles exclude toilets. We assume that adding toilets will raise the costs to €1,52. TKTA (2008) estimates the cost of one carriage of a Maglev train at €12,5-15 million in 2015. These costs regard larger vehicles with about 90 seats per carriage (compared to 28 seats per HL capsule). The costs per seat, that might be a rather comparable figure, are €0,14-0,17 million for the Maglev and €0,054 million for the HL. We suppose that the costs per seat tend to be relatively high for small vehicles and assume €0,17 million for one HL capsule seat, more than the threefold of the estimation by Musk (2013). The assumed cost of a capsule is then €4,8 million.

iv) Conversion to annual costs

The capital costs discussed above are incidental costs. They can be calculated as annual costs (depreciation and interest) according to the next equation:

$$C_{b(e)} = \frac{C_{b(e)} - R_e}{L_{t(e)}} + \frac{C_{b(e)} + R_e}{2} \cdot I_t \qquad (6)$$

where

$C_{b(e)}$ is the annual capital cost of the cost element *e* (track, station, and/or vehicle);

$C_{B(e)}$ is the incidental capital cost of the cost element *e*;

R_e is the residual value of cost element *e*;

$L_{t(e)}$ is the life span of infrastructure element *e* (years); and

I_t is the interest rate (%/year).

Table 2 gives an overview of the incidental investment and the annual costs. In all cases, no residual value is assumed (R_e = 0) for all cost elements; the assumed interest rate I_t is 4%/year. The assumed life spans are a kind of average used in the EU-countries for rail and road (Ecorys transport and CE Delft, 2005).

Table 2: Investment and annual capital cost for the HL system infrastructure and vehicles

Cost element	Investment cost (10^6€/km)[1)]	Annual cost (10^6€/km)	Life span (years)
Track infrastructure			
- Pylons, solid soil	25	0,92	60
- Pylons, weak soil	35	1,28	60
- Tunnel	70	2,57	60
Station	116	4,64	50
Capsule	4,8	0,58	10

[1)] *The value 2015*

v) Maintenance costs of infrastructure and rolling stock

For the maintenance costs for tracks, stations, and rolling stock, a fixed ratio to the capital costs is assumed. There is little evidence about this ratio. The World Bank (2011) states that the variable component of rail infrastructure cost can vary from just a few percent to about 30% depending on the intensity of use. We assume that the HL system will be heavily used, leading to relatively high maintenance cost, but also that the ratio to the capital cost will be smaller than for rail because there is no physical contact between the vehicles and the infrastructure. We assume a ratio of 10%, both for infrastructure and vehicles. This means that the assumed annual maintenance costs are 10% of the annual capital costs.

vi) Operating costs

The operating costs exist of costs for staff in the vehicles and in the stations, and traffic management costs. Generally the energy costs for moving the vehicles are also part of the operating costs, but the HL is a special case. The HL system takes energy from solar panels and according to Musk (2013) the produced energy exceeds the energy consumption by the vehicles. The capital and maintenance costs of the solar panels and the transmission of energy to the vehicles are then the only energy costs.

The *costs for employees in the vehicles and stations* depend on the organization, i.e., are there employees in the vehicles, is manpower needed for ticket sales and control, and if so, how many? Obviously, also the wage level is important. We assume that in each capsule one employee is present. He/she will check the seat belts, can help in the case of problems, and possibly can provide some food and drink. The assumed staff at stations includes two employees per station. They control and possibly sell tickets and help and guide passengers. Assuming that the average operation time of a capsule is 15 hours per day, that stations are opened for 18 hours per day, and that the average working time per day of one FTE is 7 hours (including holiday and sickness absence), the number of FTE's for one capsule is 2,14 and for one station 5,14. Assuming an average annual wage of €35000, the annual operation cost for one capsule is €75000 and for one station €180000. These costs are small compared to the capital cost.

The *traffic management costs* depend on intensity of use and the complexity of the network. We simply assume that the costs equal the wage earned by one employee for each 1000 km 'double tube'. Assuming an operation time of 18 hours per day, 2,57 FTE's are needed per 1000 km; the relating annual costs are €90000 per 1000 km, or €90 per km.

vii) Overhead costs

Finally, there are some overhead costs. These exist of capital and maintenance cost of real estate, and of costs for staff. We assume that the real estate costs are marginal compared to the capital and maintenance costs of the HL infrastructure and will neglect these. In the case of the staff, we assume one overhead employee for each ten employees needed for operation. We will include these costs by adding 10% to the costs for the operational staff.

viii) Cost overview

Table 3 gives an overview of the annual unit costs. In the case of vehicles, figures are also given by seat and seat km. These make them comparable to figures for other transport systems. For the calculation of numbers per seat km, we assume 28 seats per capsule, 15 operating hours per day per capsule, and an average distance of 600 km per hour in the operating period.

Table 3: Estimated annual costs of the HL system (€/2015)

Cost element	Unit	Investment cost	Maintenance cost	Operating and overhead cost	Total cost
Track infra					
- Solid soil	Km	917000	91700	100	1010000
- Weak soil	Km	1280000	128000	100	1410000
- Tunnel	Km	2570000	257000	100	2820000
Station	Station	4640000	464000	200000	5300000
Capsule	Vehicle	580000	58000	82500	716000
	Seat	21000	2100	3000	26000
	Seat-km	0,006	0,0006	0,0009	0,008

The vehicle cost per seat-km is very low compared to the vehicle costs of other systems. Van Goeverden and Peeters (2006) calculated vehicle costs per km for the different public transport systems in the Netherlands, ranging from €0,022 to €0,058 in euros of 1993. These costs are even higher when expressed in euros of 2015, but public transport provision has become more cost-efficient since. An interesting finding in the study was, that the costs are negatively correlated to the speed of a system. The explanation is the fact that most cost components are time related which lowers the cost per km when the speed increases. Very low costs for the extremely fast HL system could then be expected. An additional explanation for the low HL costs is that the only cost component where the per-km cost increases with distance, the energy cost, is not included in the HL vehicle costs.

Price

For an economic viable system, the average price per km that the travelers pay should equal or exceed the total costs per person km. These costs depend on the local conditions and the configuration of the system, including

- Soil condition, natural barriers; the impact is illustrated in Table 3.
- Average station spacing.
- Connectivity; this defines together with the station spacing the number of stations per km track that has to be built; in the case of just one line between two stations, the number of stations per km at a given station spacing is about two times the number in a large network.
- Frequency of the services; when the service frequency increases, the infrastructure costs are divided among more services and will be lower per ride.
- Load factor of the vehicles; this is inversely linearly correlated with the costs per passenger; because of the low transport capacity of the HL (see Table 1) and the high market potential because of the very high speed (even higher than the airplane), generally a high load factor might be expected.

The costs for the track infra make up the major part of the costs. This implies a strong relation between service frequency and costs per person km. This is demonstrated by Figure 2 that shows this relation for three types of local conditions. Assumptions are a station spacing of 500 km, a high network connectivity, and a load factor of 80%. The indicated frequencies range from 15 per day per direction (an hourly service) to 180 per day per direction, which is the maximum capacity considering that the capacity is 10 departures per hour (Table 1) and there is no or hardly any demand and supply at night.

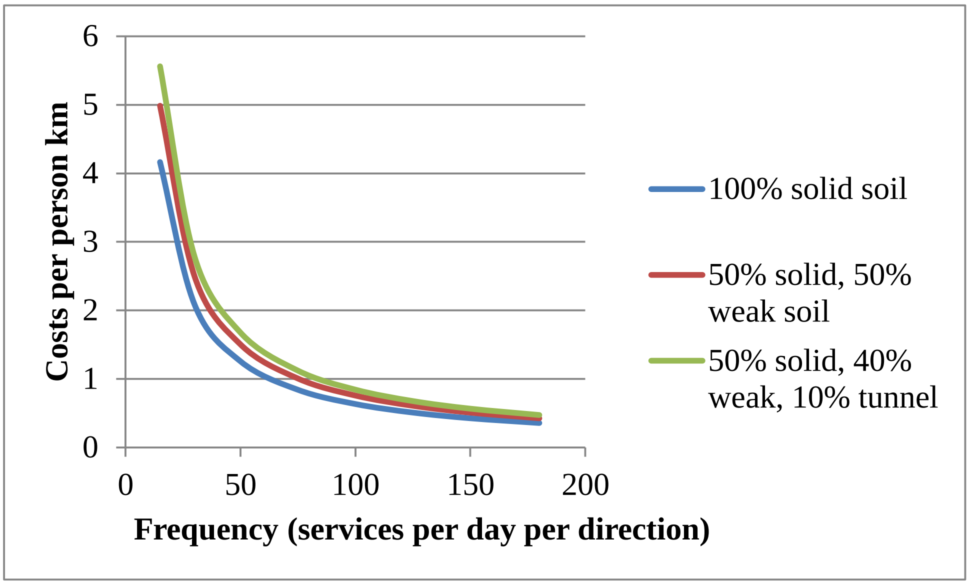

Figure 2 Relation between costs per person km and service frequency

The lowest costs (and cost-meeting fares) in the figure, in the case of 180 services per day, are €0,36 in the case of solid soil along the whole route, €0,42 in the case of 50% solid soil and 50% weak soil, and €0,47 in the case of 50% solid soil, 40% weak soil, and 10% tunnel. A comparison with the fares of alternative modes is difficult because there is generally a wide range of fares for the same route because of revenue management. Based on the experiences of De Decker (2013), the most common fares for high-speed trains would be between €0,15 and €0,25 per km, and those for conventional long-distance trains about half the HSR fares. The fares for low-cost airlines are also significantly lower than the HSR fares.

Cost calculations for a still not existing transport system are inevitably highly uncertain. However, the cost calculations produce one strong result: the costs are predominantly determined by the costs for the track infra, and therefore a high service frequency combined with a high load factor is needed for cost-meeting fares that are more or less competitive to those of the alternative transport modes.

3.3 Social and environmental performance

The indicators of the social and environmental performances of the HL system include noise, safety, energy consumption and related emissions of GHGs (Green House Gases), and land use.

Noise

Noise produced by transport vehicles can cause annoyance and harmful effects to people living and/or working close to transport routes. Moreover, traffic noise limits the possible use of space along the routes, and hence may cause an opportunity cost regarding land use. The impact of noise depends on the noise levels at sources, the number of people exposed to them, and duration of the noise exposure. This implies that this performance at the considered systems mainly depends on the routing of transport lines and speed and number of passing by vehicles.

The HL is supposed to hardly produce any external noise affecting relatively close population. This is due to the fact that the HL is not in contact with the tube and therefore there is no transfer of vibration. Any noise from the capsule itself will not be heard outside the tube and the low air pressure inside the tube prevents noise from moving the capsule. The only potential source of noise could be the vacuum pumps, but these are assumed to produce negligible noise (Wilkinson, 2016).

Safety

In evaluating the performance of a transport system a distinction is usually made regarding the internal and external safety. The internal safety relates to risk and damage caused by incidents to the users/operator of the transport system itself. The external safety reflects the possible risk and damage of accidents/incidents to people and their living/working environment outside the systems. The HL system is a dedicated and closed transport system, excluding any kind of interaction with other transport modes and its direct environment. Hence there are no external safety concerns, giving the HL system seemingly an advantage over its prospective counterparts - APT and HSR.

Internal safety benefits are expected because HL is a completely automated system and hence excludes the possibility of human errors. The HL claims to be designed according to the fail-safe-principle: in case of danger (e.g., a rapid depressurization in the capsule or tunnel), the “clever” systems will stop the capsule and, if needed, will provide means of individual salvation (e.g., oxygen masks for passengers). However, many safety issues still need further consideration, elaboration and testing, such as for example, evacuation of people, stranded capsules, incorporation of emergency exits, etc. (Taylor et al., 2016).

Energy consumption and emissions of GHGs (Green House Gases)

The HL system is expected to be less energy demanding compared to the HSR mainly due to having less friction with the track(s) and low air resistance due to the low pressure in the tube. Some preliminary estimates have suggested that the HL system can be about 2-3 times more energy-efficient than the HSR, and depending on transport distances, about 3-6 times more energy-efficient than APT (Taylor et al., 2016). This is mainly because the HL system is intended to be completely propelled by the electrical energy obtained by the solar panels on top of the tube(s). These are claimed to be able to generate more than the energy needed to operate the system. This also takes into account that sufficient energy can be stored (e.g., in the battery packs onboard the vehicles) to operate the system at night, in periods of cloudy weather, and in tunnels (Musk, 2013).

In general, emissions of GHGs are directly related to the energy consumption. If only emissions of GHGs by operations are considered, regarding the above-mentioned primary energy source, the HS system will not make any of them. However, this is if the indirect emissions from building the infrastructure (lines and stations/terminals), rolling stock (capsules), and other equipment are not taken into account.

Land use

In general, land used to facilitate transport systems cannot, except for underground transportation, be used for other purposes, hence creating an opportunity cost. The valuation of land occupied by the HL system will be a function of the space that is needed (width and length of the infrastructure) and the value of the land. The latter will depend heavily on the specific routing of the line. On the one hand, the HL system is planned to be elevated on pillars, so the effective land occupation on the ground (net area of land needed) can be limited. On the other hand, it remains to be seen if the space between the pillars can be used meaningfully. Moreover, the elevated construction may bring along visual pollution. In general the total amount of land (gross area of land) required for new transport infrastructure can be minimized by maintaining the route as close as possible to the existing transport infrastructure. The HL system’s tubes will be mounted side by side on elevated pillars. Each pillar that carries two tubes is about 3,5 meters wide (Wilkinson, 2016). The fact that the pillars will be spaced averagely 30 m will most likely limit the possibilities to use the space on the ground effectively. Consequently, the net area needed for 1 km of HL system’s line could be about 0,4 ha. The average gross area of taken land by the line is estimated to be at most 1,0 ha/km. Despite of more efficient land use of the HL system, it is likely that it will have higher cost of land than for instance HSR. This is because the HL is less flexible than HSR in routing the line particularly in terms of accommodating to the sharp turns.

4. Overview of the performance indicators

An overview of estimated indicators of performances of the HL, APT, and HSR system considered as potential competitors in the medium-distance passenger transport markets(s) of the length of 600km is summarized in Table 5.

Table 5: Indicators of performances of the HL system and its APT and HSR counterparts

	Unit	HL	APT	HSR
Considered distance	Km	600	600	600
Operational performance				
Capacity	Seats/veh	28	130	1000
	Veh/h	10	3	12
	Pax/h	280	390	12000
Technical productivity[1)]	Seat-km/h^2	341600	323710	4200000
Quality of service[2)]				
– travel time	Min	40,3	98,5	138,9
– frequency	Dep/h	10	3	12
– interconnectivity		+	++	++
– reliability		+++	+	++
Financial performance				
Costs				
– Line infrastructure	k€/year/km double track	825-2300	600	883,4
– Access points	k€/year/access point	4000	-	-
– Vehicles	k€/year/seat	29	48,8-65,4[3)]	2-4,7[3)]
	€/seat-km	0,008	0,033-0,035[4)]	0,031[4)]
Revenues/fares (€/p-km)	€/p-km	> 0,35	0,183	0,174
Social and environmental performance				
Energy consumption[5)]	kWh/p-km	< 177	591	177
GHG (CO_2) emissions[6)]	g./p-km	0	120	40
Noise[7)]		+++	++	+
Safety[8)]		+++	+++	+++
Land use[9)]	ha/km (net)	0,4	15	3,2-3,5
	ha/km (gross)	1,0	-	3,2

+: low performance; ++: moderate performance; +++: high performance

Notes:

(1) HL: 28 seats · 10 veh/h · 1220 km/h; APT: 130 seats · 3 dep/h · 830 km/h; HSR: 1000 seats ·12 trains/h ·350 km/h (Taylor et al., 2016);

(2) See Table 1; As reliability is concerned, both HSR and APT can be affected by weather conditions (e.g. ice, snow), but APT seems more vulnerable than HSR.

(3) Boeing 737 and Airbus A320 aircraft (thttp://planes.axlegeeks.com/compare/230-269/Airbus-A320-vs-Boeing-737-800); Siemens Velaro HS train (http://www.railway-technology.com/projects/siemens-velaro-high-speed-trains/) (Amortization period: 25 years);

(4) European airlines (ECC, 2015); European HSR (UIC, 2010) (Load factor: θ = 0,80);

(5) The values for the HSR relate to the European context, and are based on a mix of the energy sources;

(6) Emission of CO_2 by HSR could actually also drop to zero if electricity is produced emission free. The emissions of CO_2 by APT reflect those of the flight of 500-600 km (120 gCO_2/p-km) by an Airbus A320 aircraft (ICAO, 2016);

(7) The noise exposure of an observer at 25 m distance of a passing by HS train (depends on the train's speed) is in the range of 84-105 dBA; noise exposure by APT locally (at the airport noise measurement locations) is in the range of 46-92,5 dBA.;

(8) The number of traffic incidents/accidents and related personal injuries and deaths is expected to be at the comparable high level (Janić, 2016);

(9) Only the land use regarding the line infrastructure; (A different values can emerge when the suprastructure (i.e., stations, airports) is considered; Airports need much space compared to the HSR and HL stations

As can be seen, some indicators are expressed in quantitative and others in qualitative terms, the latter based on a relative performance, i.e., relative ranking the transport systems at three levels - low, moderate, and high.

5. Conclusions

Hyperloop is a new mode of transport that claims to be a competitive and sustainable alternative for long-distance rail transport (high speed rail) and medium-distance air transport (less than 1.500 km). Taking into account that the performance of HL can be considered in different ways and from the perspectives of different stakeholders (i.e. travelers, transport operators, government authorities and society at large) we have addressed and evaluated the performance of HL according operational, financial and social and environmental performance criteria.

In comparing HL with HSR and APT we found that HL has a relatively strong performance on the social and environmental performance criteria, in particular energy consumption, GHG emissions and noise. The HL system can potentially be a very safe mode, but both HSR and APT have also a very good safety track record.

A major weak point of the HL technology is the low capacity, mainly due to the small vehicles. This worsens both the operational and the financial performance. As a result of the low capacity, the investment costs of HL infrastructure make up a large part of the total costs per seat-km, increasing these to a higher level than those for HSR and APT. Break-even fares will also be higher, even when the load factor is high.

This finding suggests that HL-application may be limited to the premium passenger transport market, in which there is 'willingness to pay' for the strongest feature of HL, i.e. its very high average speed.

So far the HL technology is in its infancy and there are still many uncertainties around the system that need further exploration. An important research issue is, how the conditions for HL can be improved by increasing the capacity, for instance by train formation of vehicles. The capacity increase of the system would improve the operational and financial performance of the HL system.

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