WARSAW UNIVERSITY OF TECHNOLOGY Index 351733 | DOI: 10.24425/ace.2022.140153
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING | ARCHIVES OF CIVIL ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945 | Vol. LXVIII ISSUE 1 2022

© 2022. Henryk Zobel, Anna Pawlak, Marek Pawlik, Piotr Żółtowski, Radosław Czubacki, Thakaa Al-Khafaji. pp. 5 –26

This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits use, distribution, and reproduction in any medium, provided that the Article is properly cited, the use is non-commercial, and no modifications or adaptations are made.

Review paper

Hyperloop – Civil engineering point of view according to Polish experience

Henryk Zobel[1], Anna Pawlak[2], Marek Pawlik[3], Piotr Żółtowski[4], Radosław Czubacki[5], Thakaa Al-Khafaji[6]

Abstract: Idea to travel faster and faster is as old as human civilization. Different ways were used to move from point to point over centuries. The railways, cars, air-plains and rockets were invented. Each of them have limitations and advantages. Therefore, people always look for other, better solutions. One of them is "vacuum rail" moving inside a tube, known also as a Hyperloop. The number of problems to be solved is extremely high. This paper is devoted to civil engineering problems only e.g. viaducts, tunnels, stations. It is necessary to consider the kind of sub- and superstructure supporting the tube, influence of changes of ambient temperature and solar radiation, the way to ensure safety and structural integrity of the structures in case of fire, decompression of a structural tube and air-tightening, occurrence of accidents etc. Taking into account the fact that bridge and tunnel standards do not include information relating to above mentioned problems it is interesting to determine rules for design, construction and maintenance of such structures.

Keywords: high speed transportation, hyperloop, requirements for infrastructure, tubes, bridges, tunnels, stations

[1]Prof., DSc., PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: h.zobel@il.pw.edu.pl, ORCID: 0000-0002-4227-0506
[2]MSc., Eng., YLE Inżynierowie Co., Warsaw, Poland, e-mail: a.pawlak@yle.com.pl
[3]DSc., PhD., Eng., Railways Institute, Warsaw, Poland, e-mail: m.pawlik@il.pw.edu.pl, ORCID: 0000-0003-3357-7706
[4]MSc., Eng., YLE Inżynierowie Co., Warsaw, Poland, e-mail: p.zoltowski@yle.com.pl
[5]PhD. BSc., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: r.czubacki@il.pw.edu.pl, ORCID: 0000-0001-6502-5864
[6]PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: th.alkhafaji@il.pw.edu.pl, ORCID: 0000-0001-5431-2139

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

1. Introduction

The idea of traveling faster and faster is as old as human civilization. Different ways were used to move from point to point over centuries like waking, riding, sailing, railways, cars, airplanes, space shuttles. Hyperloop, proposed as new mode of transportation, has its own challenges and limits related to the vehicle, infrastructure and operations.

Hyperloop is a mode of transportation, where hypervehicle may travel free of air resistance or friction, inside a tube at high speed. Hyperloop could carry both passengers and freights. Hypervehicle should combine all advantages of traditional transportation modes eliminating at the same time their disadvantages. Foreseen most important advantages of a Hyperloop as a transport mode are: very high velocity, low consumption of energy and emissivity and frequent circulation of vehicles. The idea of Hyperloop is under investigation from many years in different countries including Poland [1–11].

Hyperloop infrastructure will be composed of tubes, viaducts, tunnels and stations. There are a lot of problems to solve but most important is to define realistic assumptions.

This paper is devoted to civil engineering problems only. It is necessary to consider the kind of sub- and superstructure supporting the tube, influence of changes of ambient temperature and solar radiation, the way to ensure safety and structural integrity of the bridge and tunnel structure in case of fire, decompression of a structural tube and air-tightening, occurrence of accidents etc.

Hyperloop idea assumes that the movement of a hypervehicle (different names are used, e.g. pod, capsule) takes place theoretically in vacuum – practically air pressure inside the tube is much lower then outside the tube but never equal to zero. This idea extort movement inside the tube. The aerodynamical resistance during movement of the pod is significantly lower than normally. The idea of Hyperloop is given in Fig. 1.

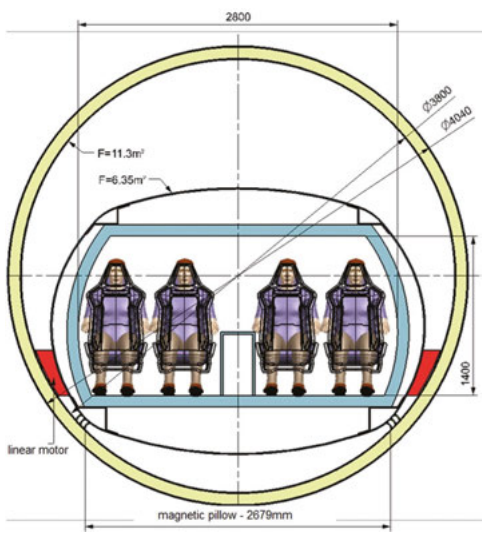

Fig. 1. The Hyperloop concept (one of many) [3]

2. Possible routes in Poland

The studies devoted to Hyperloop are on the way in some countries. They include not only "technical" investigation but also social, economic and urban analysis. The possible routes we also analysed. Proposal for Poland is presented below.

Various hypothetical Hyperloop routes were studied connecting cities in Poland with the CTH (Central Transportation Hub), which is a transport interchange between Warsaw and Lodz that is currently being planned by Polish authorities. The main foreseen goal of the CTH is integration of air, rail and road transport in Poland. Figure 2 shows a diagram of the planned connections between CTH and four Polish most populated cities, namely Warsaw, Lodz, Cracow and Katowice.

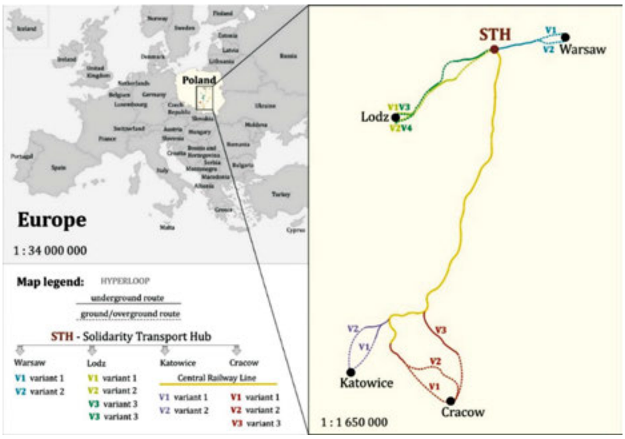

Fig. 2. The hypothetical Hyperloop routes in Poland [6]

As shown in Figure 2, for each connection between CTH and mentioned above Polish cities, at least two variants of routes were considered. In the case of the CTH – Cracow and CTH – Katowice connections, these variants differ only in the detailed plan of the route, while for routes connecting CTH with Lodz and Warsaw, different destinations have also been considered.

The length of viaducts and tunnels differs depending of the variant. Generally, in more populated areas tunnels are preferred. There is also big influence of ecological factors and land ownership on the course of the routes. Separate problem is location of stations. In the centre of the cities they have to be under ground level but near airports they could be located on the ground.

In particular, efforts were made to avoid, as far as possible the Nature 2000 sites, forests, rivers, large concentrations of people (so as not to demolish houses and imply a need for buying heavily built-up areas). An important assumption was not to interfere with the surroundings but at the same time optimize the route so that the curvature of the route does not constitute a speed limit. Generally, from technical point of view, the straight sectors of the route should be as long as possible, Table 1.

Table 1. Examined variants of Hyperloop lines in Poland [6]

Connection	Variant	Total length of viaducts [km]	Total length of tunnels [km]	Total length of the route [km]
CTH – Warsaw	1	14.552	21.359	35.911
	2	14.552	21.096	35.648
CTH – Lodz	1	24.765	58.433	83.198
	2	24.765	65.263	90.028
	3	49.308	37.879	87.187
	4	49.308	44.709	94.017
CTH – Cracow	1	242.011	47.104	289.115
	2	242.011	55.426	297.437
	3	220.488	34.369	254.857
CTH – Katowice	1	205.400	30.990	236.390
	2	223.982	30.990	254.972

In addition, the lengths of the proposed routes are representative for the typical distances between main Polish agglomerations. The second selection criterion was to ensure that there will be a significant demand on using the proposed routes by passengers (selected connections are characterized by a high passenger traffic on both traditional railway and roads). In addition to being able to transport people from the largest Polish cities to the planned CTH, the routes connecting Lodz and Warsaw with CTH will also provide more than 100-km-long direct connection between these two agglomerations in Poland.

3. Conditions and assumptions

3.1. Kantrowitz limit

The primary factor to be considered in the Hyperloop is known as a Kantrowitz limit. It determines maximum speed for a given tube taking into account cross-section area left when pod is operating. When the pod travels at a high speed through the tube, the theoretical concept of describing the choked flow comes in. When the air inside a tube experience rapid reduction of the free area, the speed of flow increase in order to maintain the same mass flow rate. So the flow choke happens at the maximum amount of contraction and the flow speed cannot be increased more than this limit.

The concept of Kantrowitz limit in Hyperloop is that the pod travels at high speed inside a partial vacuum tube/low-pressure environment. According to the continuity principle, when the pod travels inside the tube the air must speed up, while the movement of air happens in the small cross-sectional area between pod and tube. The speed of pod travelling inside the tube under a low-pressure environment could be near to the speed of sound, where the pod may attain the choked flow due to large air resistance formed around it.

There are different possibilities to overcome the Kantrowitz limit. In the first method, the tube diameter is increased to create more space for the air around the pod to eliminate the choke flow. The second method is to provide a turbine on the pod to push the displaced air across the pod's surface and hence impacts are reduced. They are also other methods. Generally, it is necessary to perform cost/benefit analysis to choose optimal option.

3.2. Air pressure in the tube versus velocity of the vehicle

The most important assumption, which is required is presumably maximum velocity of the vehicle. This is strictly combined with the "level of vacuum" meaning value of the air pressure inside the tube. The factors influencing maximum velocity of the pod were presented in Fig. 11.

The design of geometry of the track could be done applying method used for design of express ways or railway tracks for high speed trains. The track consists of straight sectors, arcs and transition curves. It is important to consider horizontal and vertical arcs. Their parameters depend on assumed velocity of the pod. It has an influence on value of centrifugal force and superelevation.

The Hyperloop travels inside the tube under a low-pressure environment. In order to create a low-pressure environment within the tube, vacuum pumps are used. The expected pressure inside the tube is 100 Pa which is 1/1000 of the atmospheric pressure on Earth [6]. Spontaneous decompression due to air leakage can lead to unacceptable stresses in vehicles constructions and even to collisions between pods and have to be seen as dangerous for passengers. The pod has to be designed in such a way that it can resist aerodynamic load. Vacuum pumps are used to create the low-pressure state, the number of pumps required depended on distance and the air-tightness of tubes and their connections. The leakage is an important factor as it occurs through the welds, collars, rings, airlocks, etc. So the vacuum pumps should work constantly to maintain the low-pressure.

Automatic shutters are required inside the tube section, which reduce the impact during spontaneous decompression, vacuum pump failure, etc. As the hypervehicles are traveling in a low-pressure environment, the pressure maintained inside the tube should rise and drop, and also the airflow should accelerate and decelerate around it. Moreover the pressure and propulsion are interrelated. To maintain low-pressure inside the tube vacuum pumps requires more energy so that it can create a low drag force and hence less energy for propulsion would be required. So the low-pressure inside the tube can be maintained depending on the number of pods traveling inside the tube.

3.3. Actions on the structures

Depending on the kind of drive of Hyperloop vehicle (e.g. electric, magnetic) and location of the track (viaduct, bridge or tunnel) following loads will be applied to the structure:

– Dead load of tube.
– Service load (of vehicle).
– Wind load.
– Thermal actions.
– Accidental loads.
– Action during execution.
– Fire loads.
– Pressure variations (inside and outside of tube).
– Dynamic actions generated by moving hypervehicles.

Depending on kind of way of mounting of the vehicle (on wheels, on magnetic or air cushion) rolling resistance has to be overcome. Because the space inside the tube is very limited additional effects occurs as a result of air compressibility. This phenomenon limits velocity of the pod. Velocity of the flow rise around the pod and finally gain velocity of sound. This causes blocking of air flow on the critical level and rise of the pressure on the front of the pod. Then the pod moves forward together with rising volume of the air.

3.4. Geological condition

During the pathway optimization, the geological conditions on the surface and beneath the surface vary. Whole infrastructure (tunnels, piers, viaducts, bridges, stations) have to be designed and constructed separately for particular geotechnical conditions. A detailed geological survey should be made for pathway optimization. This ensures the types of the pathway and the possibilities of gradients and curves could be defined which could minimize the obstacles during the execution of the project.

3.5. Thermal expansion

Air-tightness of the tubes connections is a fundamental problem to be solved for Hyperloop project. This phenomenon depends mostly on seasonal and daily differences of temperature. The natural temperature variations causes tubes to change its shape and size and produce their expansion and contraction. Typically, the top region of the tube would be liable to daylight.

Rapid decompression of tubes is very dangerous from exploitation point of view. The selection of the system of collars and kind of elongation joints will influence safety of the passengers, capsules and whole infrastructure. Other important factors which should be taken into account are structural material of the tube, value of air pressure inside the tube, propulsion of hypervehicels and range of temperatures acting on the tubes. Also the wind speed and its direction is important for whole infrastructure (i.e. piers and tubes placed on them).

Elongation joints should be design with the spacing dependent on kind of structural material of the pipe (steel, concrete, composite polymer etc.). Steel is adequately sufficient to provide the best close vacuum perfect conditions. For steel and composite polymer tubes, expansion joints should be provided at every 20÷25 m.

Thermal expansion can be avoided if the tubes are located underground but this might be not suitable for all locations.

4. Civil engineering structures

4.1. Introduction

Hyperloop infrastructure consists of tubes, viaducts, bridges, their piers, tunnels and stations. It is necessary to assume following parameters of them:

- Kind of material of tube (steel, concrete or composite polymer).
- Length of the tube.
- External diameter of the tube (each one for separate direction, rescue tubes etc.).
- Thickness of the tube wall or internal diameter of the tube.
- Number of tubes.
- Kind of structures supporting the tubes (e.g. ordinary viaduct or piers only).
- Spacing of piers.
- Height of piers.
- Tunnels (construction technology depends on geotechnical conditions and depth of placement).

Proposed infrastructure configuration and its service parameters as well as costs are strongly dependent on initial choices. At the initial stage of infrastructure studies no configurations shall be disregarded. It is assumed that single steel tube on piers is simplest minimum viable product. It is possible that other solutions might provide better construction economy, velocity of the vehicle or lower maintenance requirements.

4.2. Hypervehicle and tube dimensions

The pod (capsule) is the vehicle that travels inside a tube maintained at a partial vacuum/low-pressure environment. The dimension may differ depending on the pod type. According to Hyperloop transportation technologies the length of the pod is $5.0 \div 30.0$ m and the diameter of the pod is around 3.0 m. The tube diameter ranges from $3.5 \div 5.0$ m. The thickness of the wall of tubes may vary depending on the circumstances, materials, etc. Steel or composite polymer tubes would be directly supported by piers or placed on the deck of the viaducts. Concrete tubes would be formed as a “filling” of tunnels, which could be drilled using different, well known and used methods.

The tube size must incorporate with the speed of air as it passes around the pod. Therefore, the area of the tube cannot be considered as an independent variable as it has to be incorporated with the Mach number. It is a dimensionless quantity that represents the ratio of flow velocity past a boundary to the local speed of sound.

The dimension of the tube could be less, while the air goes in and around the pod and reduces the blockage of flow and maintains the pod at the maximum speed. The pod needs an inlet compressor, placed in the front of the pod and an outlet at the rear end of the pod creating a flow of air passing through the vehicle.

The alignment of the pathway includes gradient, banking angle and curves depends on topographical location. These elements should consider centrifugal force and also the passenger's comfort and safety. The curve radius has an influence on the lateral g-force, where g-force above 0.5 is not considered as comfortable for the passengers. Steep gradients and narrow curves in Hyperloop transportation should be avoided. As the pod travels inside a tube at 1200 km/h, the possibility of collision with the tubes in case of steep gradients and narrow curves is high.

Consideration regarding the weight, energy, pod size etc. is important. While bend radii for the Hyperloop create the relationship with the turn radius and the vehicle velocity. At the maximum speed 1200 km/h, the required minimum bend radius of 23.5 km is considered to be comfortable for the passengers while for the minimum speed of 480 km/h, the bend radius is 3.67 km [3].

Switch over ramp should be provided with low gradients for the transition from underground to overground/ground level/shallow below the ground level and vice versa. The pathway optimization should minimize the gradients and curves and maintain a straight line that could decrease the travel time and hence the pods can maintain the maximum speed.

4.3. Tube section

4.3.1. Dimension and properties

There are several options of the structures of tubes considered. Generally, each tube consists of the body and rings (collars) with stiffening rings (Figs. 3 and 4). Tubes of the Hyperloop would be directly supported by piers or laid on the deck of the viaducts or bridges. Another solution is placing them directly on the foundation or inside the tunnels.

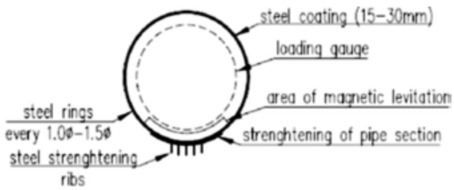

Fig. 3. The proposal of the Hyperloop steel tube cross section with magnetic levitation

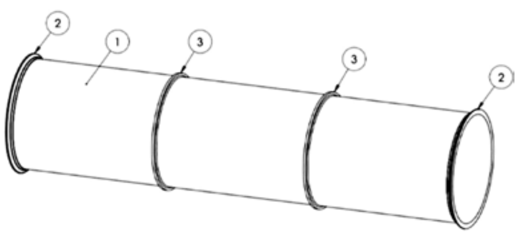

Fig. 4. Major elements of the tube: 1) surface of the tube, 2) collar connection, 3) stiffening rings

The proposed solutions are shown in Figs. 5–9.

The spacing of the piers depends on kind and weight of structural material. It is necessary to remind that concrete is 2.5 times more heavy than steel and composite polymer is 5 times lighter than steel. The most important parameter of use is deflection of the tube.

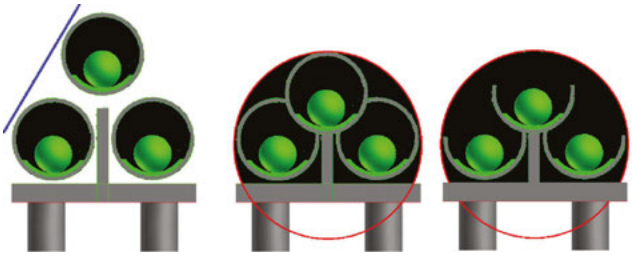

Fig. 5. The tubes could be located separately or linked together in a bigger tunnel [3]

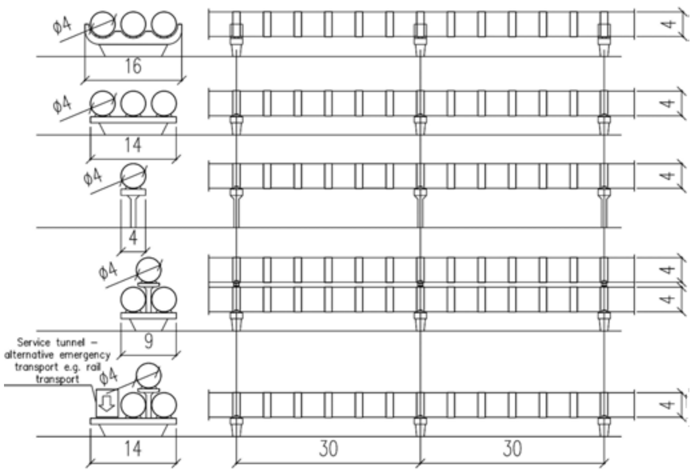

Fig. 6. Examples of the tubes supported by independent piers

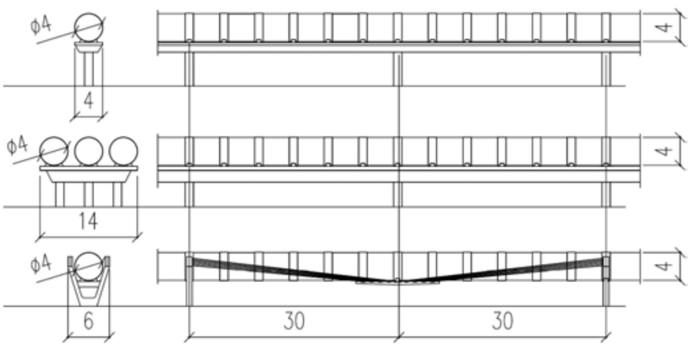

Fig. 7. Examples of the tubes placed on the viaduct or bridge

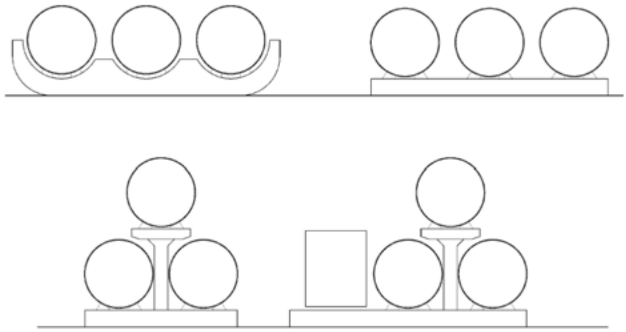

Fig. 8. Hyperloop tubes located directly on the foundation

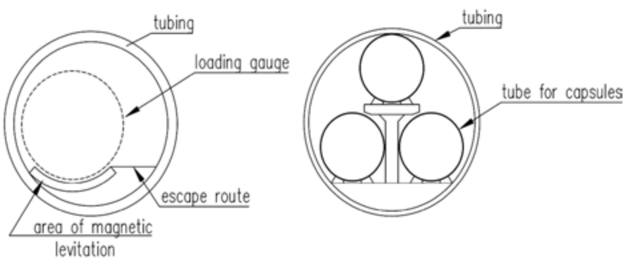

Fig. 9. Examples of the underground cross sections (on the left – independent tunnel for each separate tube, on the right – all tubes in one tunnel)

The route of the hypervehicle has to be straight and the distance from the pod to the wall of the tube should be the same along the tube. Internal space in the tube should allow easy movement of the pod.

According to current production technologies the length of tubes (steel and composite polymer) could be from 6.0 to 20.0 m. The diameter of them not exceed 6.0 m. The thickness of plates or tubes depends on production technology. At the moment it is possible to assume that required thickness will be defined when the Hyperloop would be realized.

As the pod travels inside the tube, the elements like suspension, air bearings, vacuum pumps, sub-track, solar panels, etc. are located along the tube. However, the vacuum pumps, ventilation, and repair and evacuation line are the challenges in each tube section. As the pathway for Hyperloop depends on the circumstances, for an underground tunnel, the possibility for ventilation, vacuum pumps, repair, and evacuation lines which require additional track, each section should consist of two separate tubes for two traveling directions and a separate tube for repair and evacuation.

In order to create a low-pressure environment within the tube, vacuum pumps are used. The vacuum pump consists of two elements: backing pump which reduces the pressure to 1% of the atmospheric pressure and the root pump which reduces it to 0.1% of the atmospheric pressure. So in the underground tunnels, the tubes cannot be laid directly on the surface. Instead, it needs a combined tunnel for two tubes and repair/evacuation line.

Three kinds of transportation systems are taking into account: on rails, on pneumatic wheels and using magnetic levitation (Fig. 10). No one is chosen at the moment.

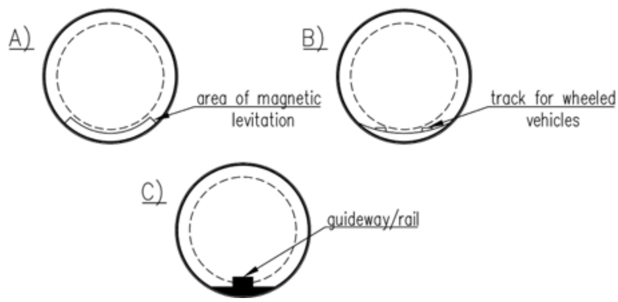

Fig. 10. Systems of capsule transportation

4.3.2. Basic requirements

Proposed, basic technical requirements of the structures and routes are presented in Table 2.

Table 2. Proposed, basic dimensions and properties of the tube

Requirements	Value
Length of the tube	From station to station
Curving of the route	radius $\geq$ 300 m
Internal diameter of the tube	From 3.0 to 5.0 m
Pressure inside the tube	1000 ± 250 Pa
Maximal time of the pumping out	24 h
Load	400 kN + dead load
Compensation of thermal elongation	Depends on the material
Maximal effluent of the tube connections	0.01 mbar l/s
Maximal time of the exchange of the tube	24 h

4.3.3. Dimensioning of the tube

The tube is the major part of the Hyperloop system. Using equations containing air parameters like pressure, temperature, density and flow velocity it is possible to define relation between the proportion cross section of the pod to cross section of the tube and velocity of the pod when it reaches critical value in the space between pod and the wall of the tube. The relationship between mentioned above coefficient and maximal velocity of a pod is shown in Fig. 11.

It means that the pod with cross section equal to 5.7 m^2 located inside the tube with diameter equal to 4.0 m which gives coefficient 0.45 is able to achieve velocity equal to 400 km/h.

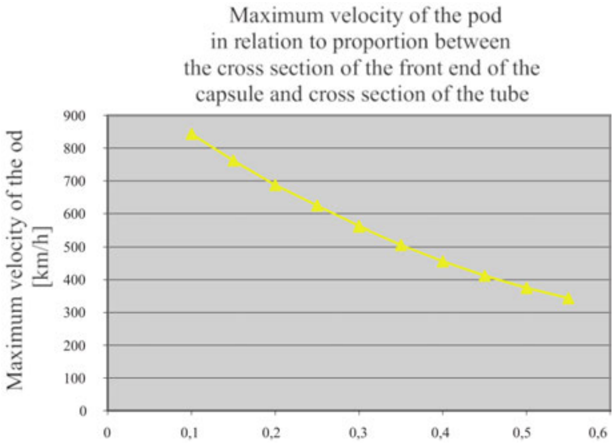

Fig. 11. Relation between maximum velocity of the capsule and proportion between the cross section of the capsule to cross section of the tube and velocity of the capsule when it reach critical value in the space between capsule and the wall of the tube [3]

When diameter of the tube is 4.5 m and the coefficient is 0.36 then maximum velocity reaches 490 km/h. When diameter of the tube is 5.0 m and the coefficient is 0.29 then maximum velocity equals 550 km/h.

There are several factors influenced by the size of the tube. The diameter should be as small as possible but it could not limit the air flow around capsule. The second factor is the value of the radius of the curve of the pathway. It depends directly on the distance between capsule and the wall of tube. The Kantrowitz limit has to be taken into account. Proportion of the tube diameter and the pod diameter is clearly shown in Figs. 12, 13 and 14 which shows pods with 2, 4 and 6 seats in row.

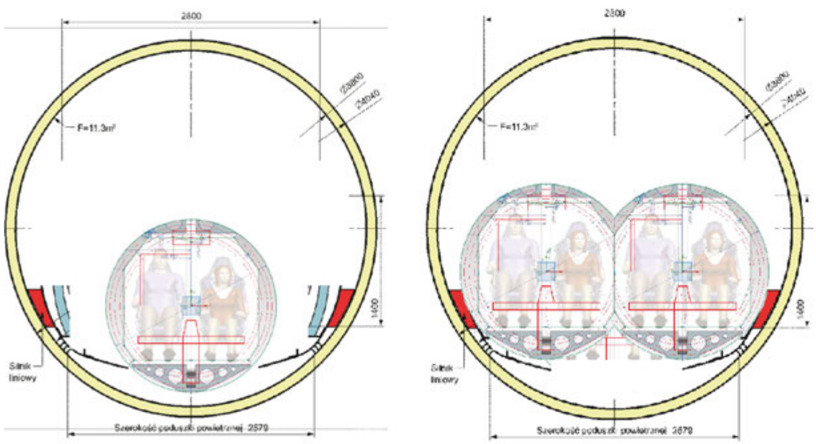

Fig. 12. Comparison of the capsule with 2 seats to capsule with 4 seats located inside tube with 3.8 m diameter [3]

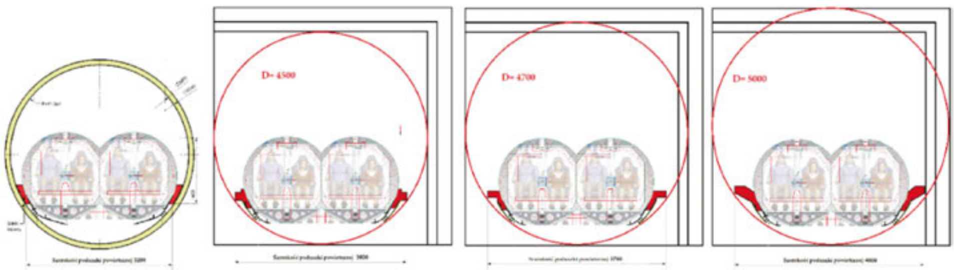

Fig. 13. Location of the capsule with 2 seats inside tubes with the diameter equal to 3.8, 4.0, 4.7 and 5.0 m [3]

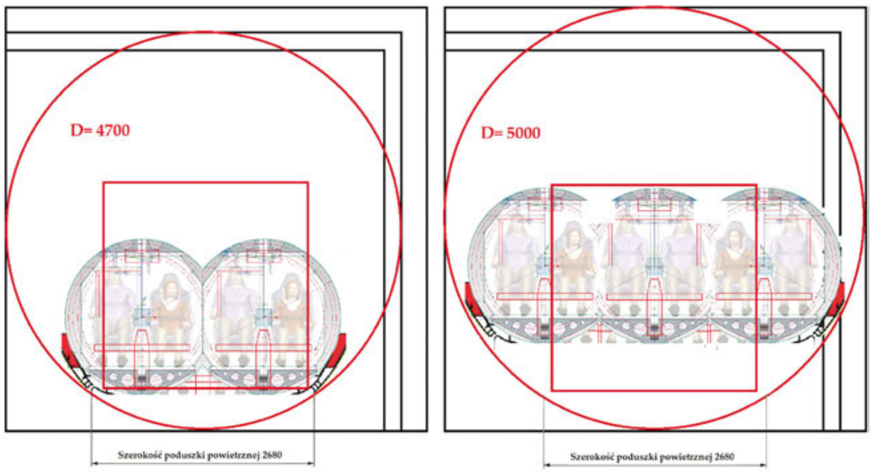

Fig. 14. Comparison of the capsule with 4 seats inside the tube with 4.7 m diameter to the capsule with 6 seats located inside tube with 5.0 m diameter [3]

4.3.4. Limited structural analysis example

The technical feasibility and construction costs are strongly dependent on infrastructure configuration. A calculation study was performed to provide some basic information on structural parameters of various geometries. Three dominant load cases were selected to represent: pressure difference, dead load and local concentrated load from pod/tube interaction. Results of the analyses were used also to confirm draft costs estimations. From structural point of view the most important parameters which should be assumed at the beginning of design process are structural material of the tube, their number, tube diameter and thickness of its wall. The location is also very important because it is necessary to decide where the tube(s) will be placed: on the viaduct/bridge or will be supported by independent piers, which means they will be self-supported. In this last case it is very important to define spacing of piers. Static, linear and nonlinear analysis were performed using SOFISTIC software with following parameters to estimate of Hyperloop infrastructure construction cases:

– Spacing between piers: 20, 25, 30 and 35 m.
– Length of a single tube segment: 5 m.
– Tube diameter: 3, 4 and 4.7 m.
– Thickness of the tube wall: 10 and 15 mm.
– Permissible deflection: $L/1600$.
– Structural material of tube: steel S355J2.
– Permissible stresses: 200 MPa.

The boundary conditions are shown in Figs. 15, 16 and 17.

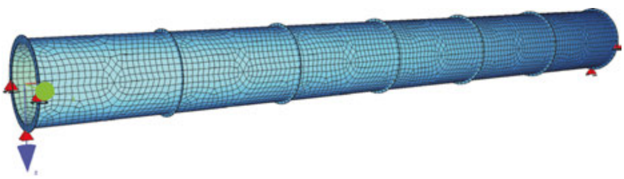

Fig. 15. $x = 0$ ($pz,\ py,\ px = 0$ on the bottom of the tube and $pz = 0$ if $z = 0$); $x = L$ ($pz,\ py = 0$ on the bottom of the tube and $pz = 0$ if $z = 0$)

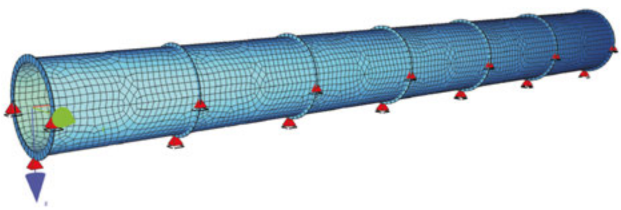

Fig. 16. $x = 0$ ($pz,\ py,\ px = 0$ on the bottom of the tube and $pz = 0$ if $z = 0$); $x = L$ ($pz,\ py = 0$ on the bottom of the tube and $pz = 0$ if $z = 0$) and every ring section $pz = 0$ on the bottom of the tube and if z

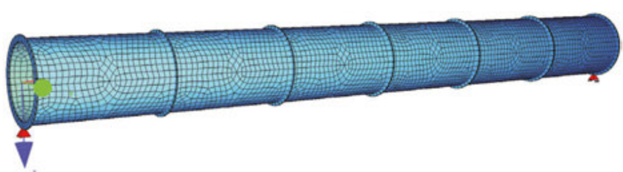

Fig. 17. $x = 0$ ($pz,\ py,\ px,\ mx = 0$ on the bottom of the tube); $x = L$ ($pz,\ py = 0$ on the bottom of the tube)

Two value loads of pod were considered i.e. 60 and 400 kN. The stability was also checked (see Figs. 18, 19, 20).

Results of mentioned above analyses are applicable to straight tubes. Taking into account stations' air-tightness related equipment and necessary vacuum equipment will probably

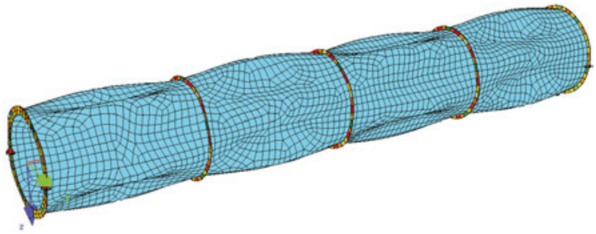

Fig. 18. Fact = 2.39; spacing of piers 20.0 m, diameter of tube 3.0 m – first buckling mode

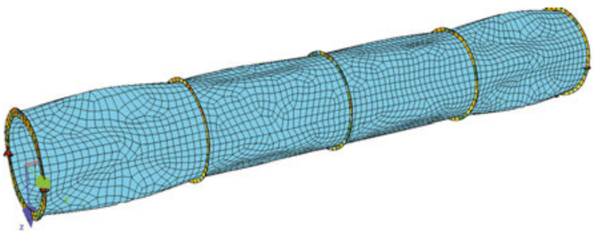

Fig. 19. Fact = 2.61; spacing of piers 20.0 m, diameter of tube 3.0 m – first buckling mode

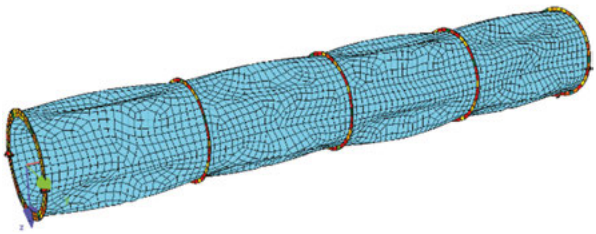

Fig. 20. Fact = 2.63; spacing of piers 20.0 m, diameter of tube 3.0 m – first buckling mode

result with significantly more complex solutions due to e.g. heavy air-tight single or double gates or many holes forming space for stations and rescue side doors, special elements for front doors blocking systems as well as route setting equipment in open air or by splitting individual tubes into more than one. Dynamic interactions will be lower in station area due to lower speeds, but construction challenges due to ensuring access to and from Hyperloop vehicles will be significant.

4.4. Hyperloop station types

4.4.1. Introduction

A station is a place where vehicles arrive and depart (Fig. 21). For the transition of passengers and freights. Each station has different features and it depends on the mode of vehicle (pod). Hence, the Hyperloop station also differs from the existing stations because of its features and creates some unique challenges. The type of station depends on the features and the requirements of the transport, city, geographical location, demand, land availability, construction methods, etc. The Hyperloop station types could be distinguished by the major features such as the number of lines connected with the station, depot area, airlocks, tracks, and warehouse area.

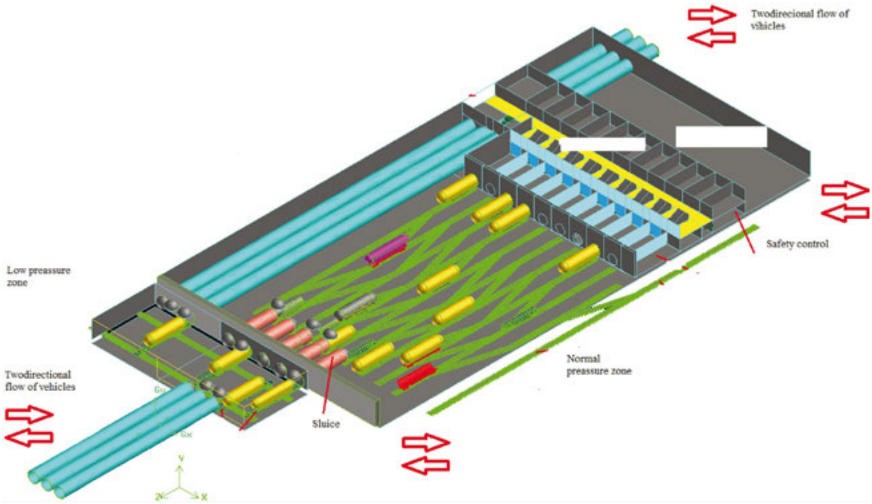

Fig. 21. One of the proposed model of Hyperloop station [3]

Lanes consist of platforms for the pods and passengers. The platform region is for the passenger's arrival and departure. Separate entry and exit to the platform creates easy access to the passengers and also minimizes the waiting haul time. The total number of lanes required in a station influence the station size and planning. The lanes can be distinguished into three forms nonstop lane, transit lane, and origin/destination lane. The station lanes are depended on the number of lines connected with the station.

4.4.2. Airlocks, air-tightness and related challenges

Someone may believe that it could be so, that whole infrastructure, namely all tubes forming Hyperloop tracks would stay closed all the time during exploitation period, which means no opening for cargo loading and unloading and no doors for access to and egress from the hypervehicles for passengers. Such assumption is not reasonable as we need transport systems to transport goods and passengers and therefore air-tightness is a big separate challenge as we need parts of infrastructure directly dedicated for loading and unloading and access to and egress from vehicles for passengers.

Taking into account different aspects of the Hyperloop system it is not possible to investigate too many air-tightness related scenarios. Therefore for two reasons following analysis takes into account passengers services only.

Hyperloop is intended to be extra quick. For passengers quicker transport system directly enlarges one day trip areas which are influencing cooperation between companies, tourism, maintaining family relationships, etc.

Passengers need access to vehicles under normal pressure and appropriate amount of oxygen in normal and in degraded operational circumstances when travelling, when blocked inside the tube and during access to and egress from the hypervehicles. Passengers need short travelling times – they cannot waste too much time neither for travelling nor for transferring from one vehicle to another in case of connections.

Therefore, it can be proposed for terminal and intermediate stations to ensure short times, normal oxygen and air pressure and air-tightness at the same time. There are several possibilities, but all of them require elaboration of detail technical solutions. Namely it is possible to have:

- **terminal and intermediate stations in an open space**, which could be ensured by:
  - **air-tight extra fast gates** opening tubes for vehicles entering/leaving stations and closing just after not too loose too much lowered pressure in tubes based infrastructure; that would however affect long distances and possibly create mechanical vibrations and noise; Appropriate reliability and availability might also be a huge challenge; Synchronization between running trains and air-tight extra fast gates and vacuum equipment is a separate possibly complex topic if we take into account safety;
  - **air-locks** instead of individual gates formed by pairs of gates which prevent spreading air along tubes by keeping air entering tubes together with vehicles within restricted areas; Air-locks for vehicles slowing down might be long not to slow down too quickly, while air-locks for starting journeys might be rather short – may be slightly longer than longest vehicles in operation; Short air-locks requiring quick slowing down from high speed in front of a still closed air-lock may be rejected from the safety point of view. Appropriate synchronization between running trains, air-locks and vacuum equipment will still necessary; Probably even more complex, but ensuring appropriate reliability, availability and safety would be easier.
- **terminal and intermediate stations forming part of the air-tight infrastructure**, which could be ensured by:
  - **air-tight front doors on a front end of the vehicles**, which could be opened only when vehicle is blocked in a terminal position; Such solution lowers significantly need for synchronization of vehicle runs and vacuum equipment; It lowers needs regarding vacuum creation performance; However it is against composing trains out of Hyperloop vehicles with virtual couplings [7] unless infrastructure ensures splitting main travelling tube into many tubes forming terminal station; Moreover having front door on one end of a vehicle imposes change of traveling direction during journey e.g. by constructing turntables turning vehicle orientation by 180 degrees just before speeding up at the beginning of a journey; Turntables may coexist with multi tube terminal station construction and virtual couplings.
  - **air-tight front doors on both ends of each vehicle**, which does not require turntables or other vehicle orientation changing solutions, but put in front a question whether sits need to be constructed in a way ensuring change of orientation by passenger. Such solutions do exist in classic passenger trains but require significant amount of space. They are usually applied in a first class coaches enabling groups e.g. four person fam-

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

ilies to travel comfortably together; Travelling full speed in case of Hyperloop having destination behind passenger's back would not be acceptable for some passengers.

  - **double air-tight side doors** enabling access to and egress from vehicles even keeping them coupled to form a train to ensure high capacity [7]; Single air-tight side doors are in use in air transport, and do not need special development, however hyperloop transportation system would require double doors like passenger lifts or driverless automated people movers utilizing platform doors systems; Such solutions are in use to ensure transport between terminals and parking places in case of big airports. Although those constructions require precise fitting of elements they were never intended to be air-tight; Such air-tightness may require side movement of the vehicle or platform door panel; It has to be remembered that vehicle outer dimensions have to be significantly smaller than tubes inner dimensions because of choked flow at supersonic or near-supersonic velocities, which have to be taken into account even in significantly lowered air pressure.

- **terminal stations in an open space and intermediate stations air-tight infrastructure**, which can ensure quick and safe access to and egress from vehicles e.g. by double air-tight side doors at intermediate stations and easy change of trains compositions by vehicles enabling ensuring connections between different Hyperloop lines without changing a vehicle in Hyperloop nodes. That would require switches enabling individual vehicles to run their own routes, and that seems to be much easier in case of stations in an open space than keeping running in such places inside air-tight tubes.

Air-tightness is also a challenge in the context of degraded situations not only when the air-tightness fails but also when the vehicle fails e.g. propulsion or power supply is not working and Hyperloop vehicle is stuck between stations. Time needed to create appropriate oxygen and air pressure conditions inside the tube for enabling rescue personnel to enter the tube and reach affected passengers cannot be long. It might be seen easy to open the tube for atmospheric pressure, but significant difference in pressure and lack of railway vehicles' crash-worthiness of the Hyperloop vehicles, which are expected to be light, as well as lack of air-pressure-wave-worthiness of the tubes, which are also expected not to be too heavy, forms additional challenges. An answer might be air-tight rescue side doors utilized together with rescue short distance low speed running to escape installations.

Hyperloop attains the high speed by the low-pressure created inside the tube. The expected pressure inside the tube is 100 Pa which is 1/1000 the pressure on Earth [6]. The station needs to consider the airlock for transferring the pod from the low-pressure (tube) to the atmospheric pressure (station) for passenger/freights exit. There are many ways to transfer the pod from the station to the tube and vice versa, but the concerns of the safety and comfort of the passengers during the entry and exit should be taken into account. The pods cannot open the door without any airlocks because of the low-pressure environment.

4.4.3. Depot and warehouse area

Hyperloop needs depot to halt the pods in the station, for loading/unloading goods and for maintenance and repair. Depot is considered as the area inside/outside the station to halt the pods. The number of pods stored in the depot depends on the size of the station and expected demand for the pods. The warehouse should be provided inside/outside the station area for freight storage. Separate connections to the warehouse should be provided in order to eliminate the intersection between passenger flow to the station and the freights transportation from the warehouse to the depot area and vice versa.

4.5. Safety and security

Hyperloop technology is a new challenge in public transportation. System is foreseen to carry thousands of people every hour. Moreover, the cost of infrastructure is also high so the security threats would be high and the impacts would be larger. The problem of failure of the pod or decompression of tube has to be solved by civil and mechanical engineers. It is necessary to design special safety vehicles, evacuation stations and emergency exits. In such dangerous, especially for people, situations which depend on the level of air pressure one or all mentioned above measures should be chosen. More detailes are given in a final project report considering Hyperloop social, technical, economic and legal context [9].

4.5.1. Tubes

The security system in case of Hyperloop should consider, that:

– Signaling and telecommunication should be provided for each pod movement to ensure safety.
– The maintenance line should be provided along the pathway in the tube as it ensures proper evacuation during an emergency situation.
– Complete screening of passengers and baggage scanning should be done in the station in order to reduce man-made disasters inside the tube/capsule.
– The emergency evacuation plan for the passengers inside the tube/pod should be developed.
– During an emergency situation such as fire/explosion inside the tube/pod, the affected pathway should be blocked until the tube/pod is recovered.
– The pod should be capable to travel in both directions. In case of an emergency situation, the pod must return back to the nearest station. The return movement might be significantly slower.

4.5.2. Station security

Hyperloop needs security screening. It increases the line haul waiting time for the passengers, but it ensures passengers safety. It is necessary to implement following actions:

– Passenger/Vistors screening in the gate using metal detectors.
– Access control for restricted areas.
– Evacuating people to a safe zone in emergency situations, especially in case of fire.
– Luggage scanning using an X-ray machine.
– Identifying and checking abandoned bags.
– Central monitoring of the station through CCTV (Closed Circuit Television).
– Non-smoking regulations should be prepared.
– Inflammable/Explosive substances should be banned.

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

- Garbage inside the station should be cleaned at a regular interval of time.
- Smoke-free evacuation route should be provided.
- A fire suppression system should be provided inside the station.
- A water pipeline should be provided to the entire station.
- Easy accessibility for passengers inside and outside the station is required taking into account also passengers with disabilities and medical emergencies.
- The number of staircases, escalators, elevations, walkways, and ramps should be determined by evaluating the passenger flow during the peak hours taking into account also emergency situations such as a fire accident.
- The gates have to be designed over the ground level in order to protect against flooding.
- Friendly features for disabled passengers should be included to maintain a sense of direction and independent use of all facilities.
- Time taken for the passenger flow from the gate, ticketing counters, security checks, baggage handling locations to the platform and vice versa should be kept minimal.
- Markings and direction boards to assist the passengers inside the station should be provided.
- The station should provide easy accessibility for the passengers to connect with local transportation systems (e.g. for agglomeration/region).
- Ramps, tactile-paving, and warnings should be provided for the elderly and disabled people from the station to the parking area/connecting points to other modes/vehicle and pedestrian pathways.
- The parking area should be provided inside or near the station area for easy access for passengers and staff.
- Pedestrians and vehicle pathways should be provided near the gates.

5. Conclusions

Hyperloop is one of the most exciting transportation project in last years. It is clear that its construction will not solve all transportation problems but in some areas it would be the best solution. The number of problems to solve is extremely high. This paper covers civil engineering problems only, which are very important from economic, environmental and social point of view. The choice of the kind of sub- and superstructure supporting the tube is crucial for safety and structural integrity of all kinds of structures in case of: decompression of structural tube, fire, occurrence of accidents etc. Taking into account the fact that bridge and tunnel standards do not include information relating to mentioned above problems it is interesting to determine rules for design, construction and maintenance of such structures.

The presented above information gives opportunity to see possible activities leading towards reasonable technical solutions and expected limits pointing as a result directions for the future research and development works.

Acknowledgements

This project was developed as a part of the gospostrateg program named "Potential for the development and implementation of the vacuum rail technology in poland in the social, technical, economic and legal context" number DWP/GOSPOSTRATEG-1/259/2018 AND GOSPOSTRATEG -1/387144/27/NCBR/2019.

References

[1] Z. Malecha, P. Krukowski, P. Pyrka, K. Skrzynecki, P. Prycinski, M. Palka, *Analysis of technological rediness transportation system using high speed vehicles in limited space with reducted air preassure. Report for National research and Development Centre – Poland*, 06.2018 (in Polish).

[2] M. Pawlik, M. Kycko, K. Zakrzewski, "Hyperloop vehicles spacing control challenges and possible solutions", *Archives of Civil Engineering*, 2021, vol. 67, no. 2, pp. 261–274, DOI: 10.24425/ace.2021.137167.

[3] J. Piechna, *Report on Conceptual Design of Hyperloop*, internal material, Warsaw University of Technology, Poland, 2020 (in Polish).

[4] K. Polak, "Hyperloop technology and perspective of implementation", *Prace Instytutu Kolejnictwa*, 2017, vol. 156, pp. 28–32 (in Polish).

[5] M. Rudowski, "Intermodal Transport of Hyperloop Capsules – Concept, Requirements, Benefits", *Problemy Kolejnictwa (Railway Reports)*, 2018, vol. 62, no. 178, pp. 55–62.

[6] R. Sabarinath, "Warsaw Hyperloop Station – Technical Challenges and Opportunities Overview", MSc. Diploma, Warsaw University of Technology, Poland, 2020.

[7] K. Trzonski, A. Ostenda, "High speed railways – technical and social aspects – Hyperloop One", *Nowoczesne Budownictwo Inżynieryjne*, 2017, no.6, pp. 86–90 (in Polish).

[8] J. Tamarit, Evacuated Tube Transportation. Sponsored by CEN/CENELEC, NEN, UNE, 12.2018.

[9] Report "Potential for the development and implementation of the vacuum rail technology in Poland in the social, technical, economic and legal context", GOSPOSTRATEG, September 2020.

[10] Hyperloop – International Development Overview, Prepared by HARDT, HYPER POLAND, TRANSPOD, ZELEROS, 10.2018.

[11] Hyperloop Alpha by SpaceX, 2017.

Hyperloop „budowlany" punkt widzenia na podstawie polskich doświadczeń

Słowa kluczowe: szybki transport, wymagania dotyczące infrastruktury, wymagania dotyczące systemu Hyperloop

Streszczenie:

Człowiek od zawsze przemieszczał się z miejsca na miejsce. Zawsze chciał robić to jak najszybciej. Dlatego wymyślił koło. Potem zastosował je w wozach, pociągach i samochodach. W międzyczasie rozwinął konstrukcje pływające, a od przeszło stu lat unosi się w powietrzu i ostatnio w przestrzeni kosmicznej. Ale ciągle poszukuje nowych sposobów przemieszczania się. Takim pomysłem jest budowa „kolei próżniowej". Pojazd ma poruszać się w rurze, w której panuje bardzo niskie ciśnienie, z prędkością zbliżoną do prędkości dźwięku. Liczba problemów do rozwiązania jest bardzo duża. W niniejszym artykule przedstawiono tylko te, które dotyczą szeroko rozumianego budownictwa, a przede wszystkim infrastruktury, tj. wiaduktów, mostów i tuneli, stacji po których lub

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

na których ma zostać ułożona rura, a w niej poruszać się tzw. hiper-pojazd. Podstawowym problemem jest zapewnienie szczelności takiej rurze, bowiem dekompresja może zniszczyć całą infrastrukturę i doprowadzić do śmierci pasażerów podróżujących hiper-pojazdami. Jest wiele czynników, które mogą doprowadzić do takiej sytuacji. Obecnie nie istnieją przepisy techniczne, na podstawie których można by projektować i budować konstrukcje dla infrastruktury Hyperloop i dlatego niniejszy artykuł jest próbą określenia stosownych założeń i wskazania sposobów ich realizacji.

Received: 11.08.2021, Revised: 13.09.2021