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A Concept of Integration of a Vactrain Underground Station with the Solidarity Transport Hub Poland

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Abstract: This paper provides an analysis of a designed underground station infrastructure for vacuum tube high-speed trains for the planned mega transport hub in Poland. The potential of integrating the infrastructure of the station building with sealed low-pressure tubes system is analyzed. The Solidarity Transport Hub Poland is a planned mega hub to be located in Baranów Municipality, Poland, which is comprised of an airport, an airport city, a road, and railway infrastructure. It is to be integrated with the first route of vactrains in Poland. The aim of this paper is to design a hyperloop station building adequate for the advanced technology of low-pressure high-speed trains. Designing a hyperloop station is not trivial, due to technological aspects which have not been hitherto present in airport or railway planning and design, such as low-pressure zones or airlocks which determine possible passenger paths and evacuation roads. Both the mega airport and Polish hyperloop are in the planning stage, therefore, in this paper, available models and designs of the hyperloop station building and infrastructure are used in order to formulate recommendations for further development and identify critical issues related to the safety and reduction of passenger transit time. The main contribution of this paper is a model of the hyperloop station building which respects the principles of spatial planning and safety standards.

Keywords: vacuum tube high-speed train; vactrain; hyperloop; spatial design; hyperloop station building; low-pressure high-speed trains

1. Introduction

This paper studies a concept of a hyperloop station in terms of effective station building and facilities with low-pressure tubes where high-speed trains go. The subject of this research is the planned mega transport hub to be located in Baranów Municipality, Poland—the Solidarity Transport Hub Poland (STH)—where a station of the first Polish vactrain track connecting the cities of Warsaw and Łódź is planned. The objective of this research is to design a safety management system and infrastructure that ensures the passengers' safety at the station with atmospheric pressure, especially during the station's interactions with low-pressure tubes while the pods are being sent or received. As the hyperloop technology has not been introduced yet in Poland, and the Solidarity Transport Hub is in planning stage, designers are relatively unlimited in developing innovative solutions that benefit from the synergy of technological advances of low-pressure high-speed train technology and the modern design of the STH.

The revolutionary feature of the hyperloop technology is the ultra-high speed of travel through the tube, thanks to the reduced air resistance; low-pressure tubes are used for moving passengers and goods placed safely in the pods or capsules. Different research groups or hyperloop companies have reached different levels of deployment of the hyperloop technology [1–8]. Very systematic and extensive literature reviews on scientific and technological developments on the hyperloop are to

be found in [9–13], while a detailed analysis of the hyperloop technology in transportation and a comparison of different means of transportation is provided in [14].

Among the advantages of the hyperloop technology, the ecological safety and the possibility to fully automate the movement are listed [15,16]. Automation is beneficial for safety management, since it excludes the possibility of human errors [14], however it makes the system complex, what causes the increase of memory and computation power needs [17,18]. This fifth mode of transportation can be a game changer in cargo delivery (freight hyperloop), as it may enable logistics companies to build a competitive advantage, due to the revolution in handling the supply chain where the delivery of goods will be performed at a speed that is characteristic of air transport and at costs that are comparable to road transport [19–23]. In the transportation of people, the advantage of the the hyperloop is the timely delivery of passengers, thanks to the flexibility of travel planning and short origin–destination travel time. Due to the high frequency of pods and ultra-high travel speed, it may be possible to introduce fully on-demand scheduling, where passengers cannot miss connections, because the schedule follows passengers' itineraries. Moreover, a small capacity of pods can enable many direct connections and provide effective short haul mobility [24–26]. The hyperloop transport system is robust and insensitive to such factors as weather conditions or intrusion into the track, and it can exclude the system from the influence of external factors (sealed vacuum tubes), thanks to its full autonomy and automaticity.

Hyperloop stations would differ from the normal train stations, due to the interactions between atmospheric pressure zones and low-pressure zones, nevertheless, similar to railway stations, it will be subjected to four main criteria: (1) means of transportation characteristic oriented, (2) passenger services, (3) architecture and urbanism, and (4) economics [27,28]. Like the railway infrastructure, the hyperloop infrastructure needs to follow the guidelines for Building Information Modeling (BIM) [29]. It is expected that the flow of the passengers would be affected by three main factors in the station: the layout and location of facilities in the station, the number of people passing through the station and their characteristics, and finally how people would find their way in the station. Two main approaches to the hyperloop station design can be identified: (1) a regular station (final or intermediate), where passengers could only get in or get off exclusively in this transport mode, and (2) the transportation hub that would combine several types of transportation modes, as the passengers could pick their type of transport outside of the station [30–32].

As the hyperloop technology is new and can only be compared to existing means of transportation, safety concerns should be taken very seriously, but also it should be communicated to the potential users that such measures were undertaken. Depending on the construction of the transport system (ground, pillar, or underground) and the technology of moving pods in tubes, numerous safety aspects need to be investigated [33–36]. The safety management system includes the evacuation of passengers from low-pressure tubes in case of emergency. Information on this aspect of Hyperloop infrastructure is scarce; this paper refers to works in which passenger safety is mentioned implicitly or explicitly. Among risk factors, the following were listed: very-high speed, acceleration/deceleration, aerodynamics, magnetic field, human factor, the effect of noise and the absence of noise in tubes, fear of accident-related injuries [30,37–41]. As a safety factor, the distance between pods was examined [24] as well as the way they enter or pass by a station or follow a complex magistral structure with switchers [32]. On an operational level, risks concerning passenger flow, embarking, and disembarking were identified; a high departure frequency needs a smooth and robust luggage handling and boarding process [42]. An interesting concept of the hyperloop safety is presented in [14], where the fail-safe-principle is adopted: in case of danger (e.g., a rapid depressurization in the pod or tube), the systems will stop the pod and, if needed, will provide means of individual salvation (e.g., oxygen masks for passengers). The same authors emphasize that many safety issues still need further consideration, elaboration, and testing, such as the evacuation of people, stranded capsules, incorporation of emergency exits, and so forth. Furthermore, increasing the complexity of relationships between humans and automation in a the hyperloop system is considered as a risk factor and requires the elaboration of new accident models, accident prevention, and risk assessment techniques [9].

Noise pollution is considered an important external effect of transportation, affecting both passengers and people living or working in the neighborhood of the transportation infrastructure [43–47]. According to the research, the hyperloop is supposed to hardly produce any external noise which would affect the relatively close population, because pods are 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 [14,48,49].

The sustainability of the hyperloop system is discussed with reference to its energy consumption [50]. This discussion covers energy efficiency of propulsion, electrodynamic [51], brakes [52,53], and capsule design [15,54], as well as renewable energy sources used for powering the hyperloop [55–57]. Preliminary research suggests that the hyperloop is expected to be about 2–3 times more energy-efficient than the high-speed railway, and depending on transport distances, about 3–6 times more energy-efficient than airborne transportation. In terms of sustainability the hyperloop is intended to be completely propelled by the electrical energy obtained by the solar panels on top of the tubes; the energy is claimed to be sufficient to operate the hyperloop system 24/7 [14,58–60]. The energy efficiency of the Hyperloop system is supposed to be improved by 60% in comparison to the high-speed railway [25,61]. Moreover, estimated direct energy consumption and related CO2 emission of the hyperloop is supposed to be lower than in other high-speed systems [62].

The project to which this paper refers comprises three tubes, so that smooth transit in both directions is assured even if a failure in the system occurs; the pods from the blocked tube are directed to the middle one. The most important issue is the use of low pressure (about 100 Pa), also called "vacuum". Low-pressure zones are deadly dangerous for people, so the fear of vacuum may discourage the number of passengers from using this means of transportation despite its obvious advantages such as short travel time. On the other hand, a lot of people are not afraid of travelling by plane although outside the plane the pressure is also extremely low (about 1000 Pa). Anyway, it is crucial to equip the hyperloop stations and tubes with safety management systems that ensure the robustness of operations and proper evacuation in case of emergency. First of all, transportation pods which go through low-pressure tubes need to be air-conditioned and equipped with air tanks whose capacity will be enough to provide oxygen to passengers in the pod in case the vehicle is trapped in a blocked tube. Secondly, it must be determined how to move such pods to the nearest emergency sector, and how to fill the sector with air so that the passengers can be safely evacuated out of the tube. The same issue refers to the situation when a pod gets unsealed.

The remainder of this paper is structured as follows: Section 2 discusses selected available concepts of a hyperloop station in various vactrains projects. Characteristic features in terms of its similarity to an airport or railway station are studied. In Section 3, the concept of the Solidarity Transport Hub Poland is briefly described with special focus on its characteristics that can be considered as arguments for using it as a location for a high-speed low-pressure railway station. The next section presents a concept of an underground hyperloop station to be located in the STH. The focus is placed on the interaction between the station building and low-pressure tubes, modern design methods, passenger flow management, and a safety management system. In Section 5, conclusions are drawn and recommendations for further research are formulated.

2. A Review of Selected Concepts of the Hyperloop Station Building

For successful implementation of the hyperloop as a means of mass transportation, the integrity of vactrains station buildings must be ensured. In many hyperloop projects, the following three aspects are considered as crucial: modern design, passenger flow management, and safety management systems. Designers and architects develop their concepts utilizing Building Information Modeling; they focus on the engineering crucial to the efficiency of the station, the quality of user's experience, and the relation between a building and the urban environment.

For instance, in several projects of the hyperloop stations for the United Arab Emirates, the designers concentrated on low-pressure sealed tubes and their interactions with three consecutive stations in the route linking between Dubai and the Fujairah emirate [63]. The main feature of the concept by Hyper Poland is compactness, which allows fitting the hyperloop stations in dense urban centers [63,64]. It is obtained, thanks to multiple floors with gantry cranes and a turntable to compact their station, shrunk station's footprint with a three-point turn. The main advantage is density station facilities and the reduction of the station by a three-point turn. The main weakness of this concept is a turntable, as it needs control, maintenance, and repairs which increases the total operational costs. In this concept, passenger pods and cargo pods are combined in multi-pod trains subject to passenger flow intensity during the day and the night. In this concept, tubes stay above the ground similarly to the monorail. Solar panels are installed on tubes to provide the system with energy. The system is designed for a modern means of transport, which is faster, safer, and more sustainable and relatively cheap for passengers in comparison to existing means of transportation.

Another concept which deserves detailed assessment is the hyperloop station by UNStudio [65], i.e., a vactrain transport hub for future transit in Europe designed by the Hardt Hyperloop for the route between Amsterdam, the Netherlands, and Frankfurt, Germany, with five intermediate stations. This is a study of how the hyperloop can be incorporated into cities and towns of different sizes and contexts. The designers envisage a symbiotic, modular approach to integrate with the local environment [65], which is the main advantage of this concept. This system is scalable, resistant, and adjusted to the surroundings. The modular structure of the transportation hub makes it adjustable to various environments: downtown, suburbs, or intermodal transportation hubs containing an international airport. As the hyperloop station building comprises underground and above-ground levels, it fits areas with low-rise buildings. The modular structure organizes and unites the station from the platforms, through the functional and social spaces, to the roof. However, there are unexplained issues such as: how does the station interact with low-pressure tubes, or what type of passenger flow management is employed in the system. Despite the concept being elegant, it may be successful only if the transport system is coherent and really takes advantage of the modular structure of the Hyperloop station building.

An extraordinary hyperloop station was designed by RB Systems for Hyperloop One's project in Dubai [66]. The spatial and programmatic concepts are largely experimental, as there are no precedents for this futuristic building typology. Due to the rapid projected turnover rate of 1 pod per minute, the design includes a difference in levels: once a pod enters the station it is carried on tracks to a platform, after the passengers and luggage are unloaded, an elevator lifts the pod to an upper level, where it is prepared for departure. All these maneuvers should be operated by an automatic dispatching system. A concrete rail shift inside the station will help to streamline this sequence and serves to dictate the station's overall layout [66]. The main strengths of this concept are the scalability of entrance/exit roads, the modular structure of the station building, and innovativeness. The scalability and modular structure of the hyperloop station building are worth copying to any hyperloop station integrated with a transport hub. The station comprises several levels, which can be considered as a weakness of the design in terms of safety management: a pod enters the station using rails, after passengers leave the pod an elevator transfers it to the upper level to prepared the pod for the next trip. Any disruption, scheduled maintenance works, or inspections may cause a blockage of the pod flow.

Contrary to the previous ones, the hyperloop station building designed by Delf Hyperloop is mainly underground—including the airlocks and tubes—so there is a need for natural lighting and the light created in the station suggests a double function, as it also becomes part of the landscape at ground level. At ground level, the station invites users to interact with the landscape designed to be harmoniously connected with public transportation such as trams and buses. As the pods arrive at a lower level (−2), passengers will de-board and be directed to the main area. Each platform will have its own check-in and security system, allowing pods to reach a 1-min departure/arrival frequency. Once the passenger is fastened to the seats, the pod moves to the airlock chambers, where the surrounding air is depressurized (near vacuum) and the interior air is pressurized for a safe and

comfortable environment during the journey. Multiple vacuum chambers would be available to grant flexibility at high peak hours of the users. With this system, passengers would have no need to wait in line for hours like at airports. The station would feel a bit more like a metro station than anything else [67]. The main advantage of this concept is the underground location of the station, which makes the design useful for new transportation hub projects which are not limited to going underground. Among the strengths can also be listed: the system of airlocks chambers and the independent check-in and security system. Nevertheless, it is challenging for the safety management that pods are taken to the departure level above (−1) by an elevator—much like those used at modern-day underground parking lots—and then transferred (through automation) to a pre-designated platform. Using elevators for pods transfer may become a bottleneck of the system, due to periodical blockages for maintenance works or inspections.

There are several more concepts of the hyperloop station building, such as designs by Mobius [68], Serge Roux [69], or young architects [70,71]. The examples discussed in this section are the most distinct and may inspire further innovative solutions for hyperloop stations. The most relevant aspects are scalability, modular structure, functionality, smooth and fast movements of pods and passengers, and safety. The concept of an underground hyperloop station building for the Solidarity Transport Hub Poland benefits from the designs discussed above in terms of adapting their strengths. Hitherto, concepts of interaction between the station and low-pressure tubes seemed unsatisfactory, so they led to the original one presented in Section 4.

3. The Solidarity Transport Hub as a Potential Location of a Hyperloop Station in Poland

In 2017, the state authorities in Poland decided to build from scratch a huge modern international transport hub called the Solidarity Transport Hub Poland (STH), which is to serve mostly as a transfer hub for passenger and cargo freight. The STH located in central Poland is supposed to act as the main transport hub not only in Poland, but also in central eastern Europe, therefore it needs to be connected with main business and industry centers [72].

The STH project includes huge investments in road and rail infrastructure. A significant assumption that underlies the concept of investing in STH is the integration of the central hub with the existing airports in Poland by means of a robust network of roads, railway, and hyperloop. The investors and designers foresee using high-speed low-pressure railways which, at the very beginning, would directly connect the STH with Warsaw, the capital of Poland. The hyperloop research teams also consider the STH as an intermediate or final stop on the first route of a high-speed low-pressure railway in Poland.

The Airport Council International (ACI) recommends connecting airports with train stations so that the railway can serve as a supplementary means of transport for short and medium distances, even if short distance connections like underground are in place. ACI uses the example of an airport in Madrid, Spain, where despite the existing underground train shuttling between the airport and the city center with the velocity of up to 120 km/h, it is planned to build a station for high-speed trains as part of the airport infrastructure [72].

The concept of building a hyperloop station in the STH is in line with the worldwide trend of using high-speed trains as a means of transport serving passengers on the routes with stops at international airports. Since 2014, the Shanghai Maglev Train (Transrapid) in China has operated as a commercial train that serves a line connecting Shanghai Pudong International Airport and the outskirts of central Pudong, Shanghai (30.5 km). It is a maglev train operating with the top speed of 430 km/h and serves 115 trips daily [73]. In 2016, the USA launched a project on a high-speed ground transportation line between Baltimore, MA, and Washington, DC, with an intermediate stop at Baltimore-Washington International Thurgood Marshall Airport. The intended speed of train is 482 km/h [73]. In the same year, also in the USA the Mid-Ohio Regional Planning Commission presented to the public a project of a Hyperloop-operated corridor for rapid transportation of people and goods linking two international airports in Chicago, IL, (O'Hare and Chicago Midway), two international airports in Columbus, OH, (Rickenbacker Cargo Airport and John Glenn), and two airports in Pittsburgh, PA, (Pittsburgh

International and Northeast Pittsburgh Airport) and considered it a game-changer in multimodal transportation [74]. In 2016, Hyperloop One started a project on a Hyperloop route connecting three major airports in the UAR: Abu Dhabi Airport, Dubai Airport, and Al Maktoum Airport [73]. In 2017, in the Netherlands, a 57-km route linking Schiphol and Lelystad Airports was selected for testing low-pressure commercial passenger transport at velocities above 1000 km/h, as it seemed economically interesting for potential commercial use [75]. In the same year, Hyperloop Transportation Technologies announced the launch of a hyperloop system implementation project in Jakarta, Indonesia, which included a road from Jakarta Soekarno-Hatta International Airport to the city center [74]. In 2018, Transport Systems Catapult proposed a Hyperloop link between Heathrow and Gatwick airports in London, Great Britain, which could offer advantages in terms of airport expansion, because with a high-speed train connection with transfer time of 10 min, Heathrow and Gatwick could be considered a single hub airport [76].

Solidarity Transport Hub Poland

The Solidarity Transport Hub Poland is a planned international transfer hub which integrates air, rail, and road transport. The STH is to be located in central Poland, 37 km west from Warsaw, and cover 3000 ha of land in Baranów Municipality [77,78]. The decision on the investment was made by the Council of Ministers on 7 November 2017 [79]. On 10 May 2018, the Polish Parliament adopted the Act on support for new investments [80]. The project should enter the construction phase in 2023 and first airplanes are planned to be served in 2028. In the very first stage of its functioning, the STH is supposed to serve 45 million passengers a year, while in the ultimate phase till 2050 this number is to increase to 100 million passengers a year [79,81]. Based on publicly available information and comparisons to other projects of this kind in other countries, the experts estimate that the airport in the STH can reach its stable profitability with 25–28 million passengers per year [82].

The STH location, investment timeline, as well as the means and methods adopted in the project were selected by the Polish government after the analysis of two main reports: (1) The Report of Inter-Ministerial Interdisciplinary Team for Selecting the Location for Central Airport for Poland prepared in 2003 [72], and (2) The Central Airport Concept for Poland—analyses prepared by the consortium of Oliver Wyman, PriceWaterhouseCoopers, MKM, and Deutsche Flugsicherung in 2010 [83]. As a result, the location of this huge airport was selected; the STH is to be sited in Baranów, Teresin, and Wiskitki municipalities, mostly in the territory of the former one. Despite its rural character, Baranów municipality has extensive road infrastructure. A2 highway and railway lines run in the immediate vicinity of the potential construction site. The selected place is also well connected with another big Polish cities, e.g., Wrocław (with S8 Expressway) and Poznań (national road No. 92) [81,84–87].

According to the Polish government, this mega transport hub has two main purposes as an international airport: (1) to serve air passenger traffic with a large portion of transfer passengers (50% of the total number of passengers), and (2) to handle an increasing volume of air cargo freight which up till now has been a small share of cargo transport in Poland [72]. With high-speed roads and direct railway connections between the STH and major Polish cities, this project affects the shape of the national transport network. This aspect of the STH project was analyzed in detail in the report of 2010. As the STH is supposed to take over the role of a transfer hub, the air connections from local airports are to be redirected to this location. The number of flights served by airports in Polish cities like Kraków, Katowice, Poznań, or Gdańsk will decrease, and the passengers will find it necessary to get to the STH quickly and comfortably to catch their flights. Therefore, the STH project includes a huge investment in railway infrastructure of a hub-and-spoke, so that a direct and quick connections between the STH and 10 major Polish cities can be established.

In the report of 2010, the experts emphasized that the STH is also considered as a potential station of a pilot high-speed low-pressure railway line connecting Polish cities: Warsaw and Łódź. In the designed systems of railway and hyperloop, the STH is considered to be an intermediate stop on the

route between Warsaw and Łódź. Instead of taking domestic flights, passengers would travel by rapid trains including high-speed low-pressure trains (hyperloop), which will have a positive effect on the environment in terms of reduced carbon footprint. The designed railway connections fit the TEN-T European transit corridors for intermodal cargo freight, therefore Poland may become an important player in the international intermodal transport system that combines land and air transport [83]. Moreover, if international passenger flow exceeds the capacity of the airport, the importance of cargo hub may increase. For that reason, having a Hyperloop connection capable of serving an intermodal cargo hub would be a competitive advantage of the STH [86].

The total costs of the investment have not been revealed to the public. According to the agency responsible for the project, the total estimated cost is PLN 34.88 billion including PLN 16–19 billion for airport infrastructure, PLN 8–9 billion for high-speed train (Warsaw-Łódź), and PLN 6.87 billion for road infrastructure [86]. However, independent experts estimate the total cost of the SHT project at PLN 100 billion, including PLN 35 billion for airport and hub infrastructure, PLN 40 billion for new railway connections between the STH and the main Polish cities, as well as PLN 25 billion for a new agglomeration, called Aerocity, that would be inhabited mostly by the STH employees and their relatives [82].

Note that the potential hyperloop station building will be situated at the STH which is likely to achieve a status symbol of Poland, so its functionality and aesthetic values should meet the highest standards [88,89]. Moreover, the general concept of STH stipulates that it should be built gradually and accordingly to the increase of demand for transportation. Therefore, it must be ready for incorporating new and advanced means of transport including the hyperloop [85]. In 2019, six concepts of the STH were presented by world class architects. All of them integrated this mega airport with railway connections and included railway stations as an integral part of the transport hub, while only 2 of them (Chapman Taylor and Foster + Partners) explicitly mentioned and vaguely included the hyperloop technology. It should be emphasized that a railway station and Hyperloop station differ a lot. Some railway stations included in the STH concept cannot be easily transformed into the hyperloop stations, as technological requirements for a vactrain station are highly advanced.

The design by Chapman Taylor with a futuristic airport city under the glass dome considers longevity and relevance of the new transport environment (see Figure 1). In this six-story building, a railway station is located at the lowest underground level. Chapman Taylor integrated hyperloop with the railway element, which they considered as significantly oversized and flexible to easily allow the introduction of future rail and hyperloop connectivity [90].

Figure 1. The Solidarity Transport Hub Poland (STH) concept by Chapman Tylor [91].

The concept developed by Foster + Partners (see Figure 2) proposes a modular design of the airport that can be adapted to the future transport requirements. The axis of the hub consists of two terminals connected with a railway shuttle. They claim they employ smart solutions and advanced technologies; however, the only use of the hyperloop is for cargo transport [92].

Figure 2. The SHT concept by Forter + Partners [92].

The final design of the STH has not yet been selected. Furthermore, it should be noted that the feasibility study has not been carried out, the master plan has not been created, and the overall budget of the STH has not yet been established.

4. Hyperloop Station Building Design

It is obvious that when designing station facilities for vacuum tube high-speed trains, the engineers and architects are obliged to follow the existing construction standards and meet requirements of the advanced hyperloop technology, as it is a completely new and challenging means of transportation. For that reason, hyperloop station building designs need to be analyzed subject to at least: modern design methods, technology, coherence of processes, and correlations between passenger flow, and train timetables.

This section analyzes the influence of modern structure and design of the vactrain station and its in-building installations and system of continuous robust operations of vacuum tube high speed trains. This study includes:

- review of the existing modern railway station buildings;
- analysis of infrastructure solutions implemented in the existing airport and railway station facilities;
- identification of specific requirements for a hyperloop station building;
- identification of specific requirements for passenger transport infrastructure;
- design of site plan of the STH with reference to the requirements for the hyperloop station layout;
- producing land development plan;
- development of the concept of a hyperloop station building and facilities with respect to special requirements of vacuum tube high speed trains, e.g., airlocks and airlock chambers;
- identification of requirements for passenger transport infrastructure;
- development of traffic flow management plan including critical safety issues and the reduction of passenger transit time.

The concept of a hyperloop station building is in line with the general concept of the STH and assumes that the vactrain station is connected with the internal transport system of the STH (e.g., airport shuttles), public transport which operates between the STH and nearby cities, and other means of transportation which transport passengers and deliver cargo to the STH, so that the STH can be considered as a single transportation hub [93]. Figure 3 shows a possible land development plan. It should be noted that the final design of the SHP has not yet been selected and no land development plan has been provided by the investors of STH, so it is not possible to determine the location of the Hyperloop station. The Hyperloop station at the STH is going to be part of Łódź-STH-Warsaw route (see Figure 4).

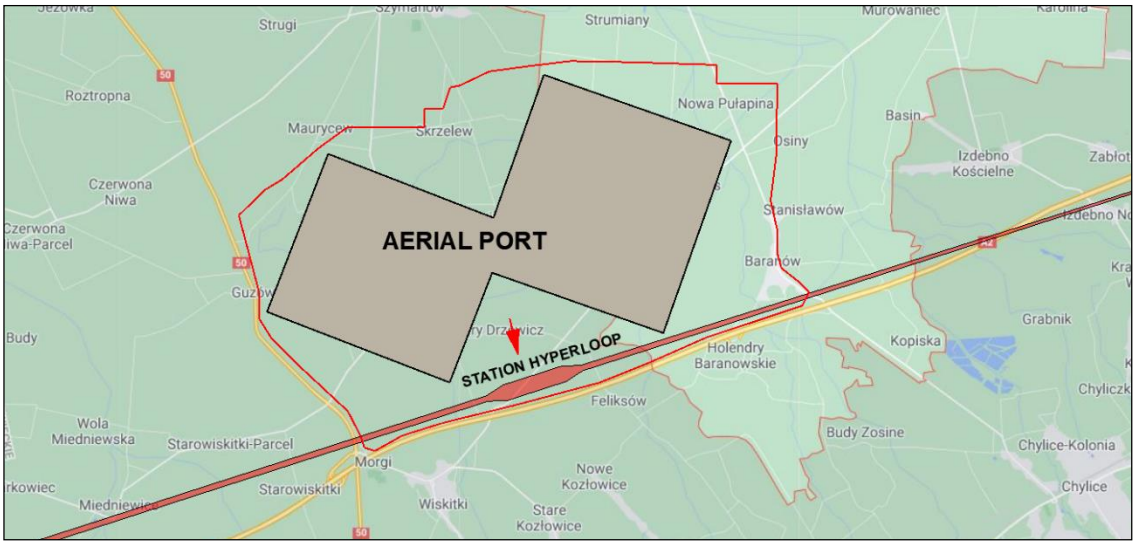

Figure 3. Potential location of Hyperloop station at the STH. Adaptation of [94].

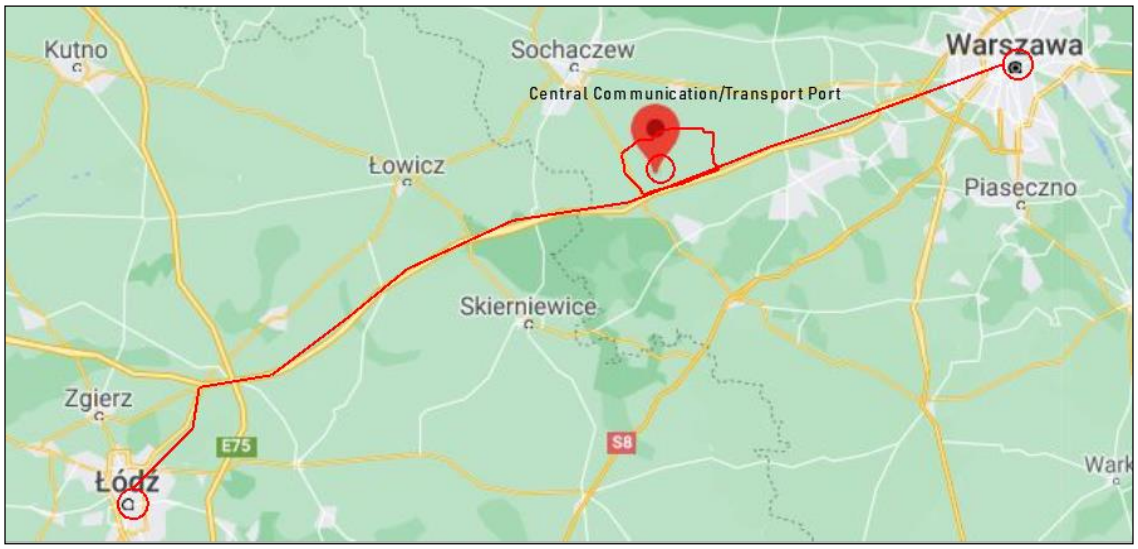

Figure 4. Potential Hyperloop route Łódź-STH-Warsaw.

In Figure 5, the cross-section of a hyperloop station building is presented. In the process of designing this station, additional guidelines for the building and the facilities structure, passenger service, as well as detailed recommendations for moving hyperloop pods in low-pressure tubes were formulated. The need for detailed specific guidelines for the construction, outward extension, alteration, reconstruction, modernization, overhaul, and complete renovation of tubes and other parts of the vactrain station facility were identified. The aim of such guidelines is to obtain a hyperloop

station building and facilities that meet all design-related standards and provide accessible transport for passengers and a safe environment for the employees of the transport hub [95].

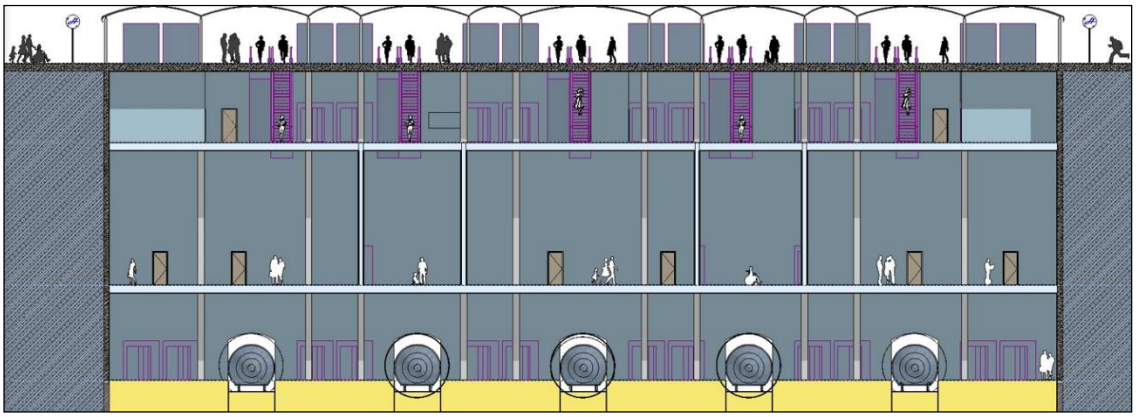

Figure 5. The cross-section of a hyperloop station building.

It should be emphasized that currently there are no specific standards on low-pressure zones at hyperloop stations, however, they will be introduced shortly, due to the dynamic development of vacuum tube trains technology. These standards should cover the following aspects:

- utilization of double-pod low-pressure high-speed trains;
- assuring safe passenger access to passenger transport infrastructure and pods operating in low pressure or vacuum tubes;
- assuring safety and accessibility of the station facilities for passengers with disabilities or reduced mobility;
- coherent guidelines for designing and operating passenger emergency platforms located in vacuum tubes.

4.1. Guidelines for Designing a Hyperloop Station Building and Facilities

The key for an effective Hyperloop station building and facilities is to integrate two components—a station building and vacuum tubes system—so that they can operate together despite significant differences between them. A Hyperloop station building needs to comply with numerous detailed guidelines. For instance, the minimal cubic space per passenger must be always respected, and traffic fluctuation throughout the day should be taken into account; the number and capacity of staff rooms must reflect the scope of technical and commercial activities to be performed at the hyperloop station. It is crucial to respect the order of design phases and follow fundamental principles and guidelines for the spatial design, so that a new, successful solution for technologically advanced means of transportation is delivered. Depending on the specific character and location of a hyperloop station building—a detached station building or a station integrated with the already existing buildings or structures—the engineers and architects need to carefully define design stages, identify relevant legal regulations, and continuously check the quality of project documentation. Moreover, the project needs to obtain a positive result of the environmental impact assessment.

Designing and running a hyperloop station building must include (see Figure 6):

- design standards and spatial, technological, and functional requirements;
- coherence of all the constituent parts, structures, and functions;
- modern construction techniques;
- safety of passenger traffic and ways to avoid life or health-threatening situations in a hyperloop station building;
- utilization of e-solutions (e-ticket, GPS, the Internet of Things);

- passenger and luggage flow management;
- utilization of renewable energy sources;
- integration and intermodality of passenger and cargo flows.

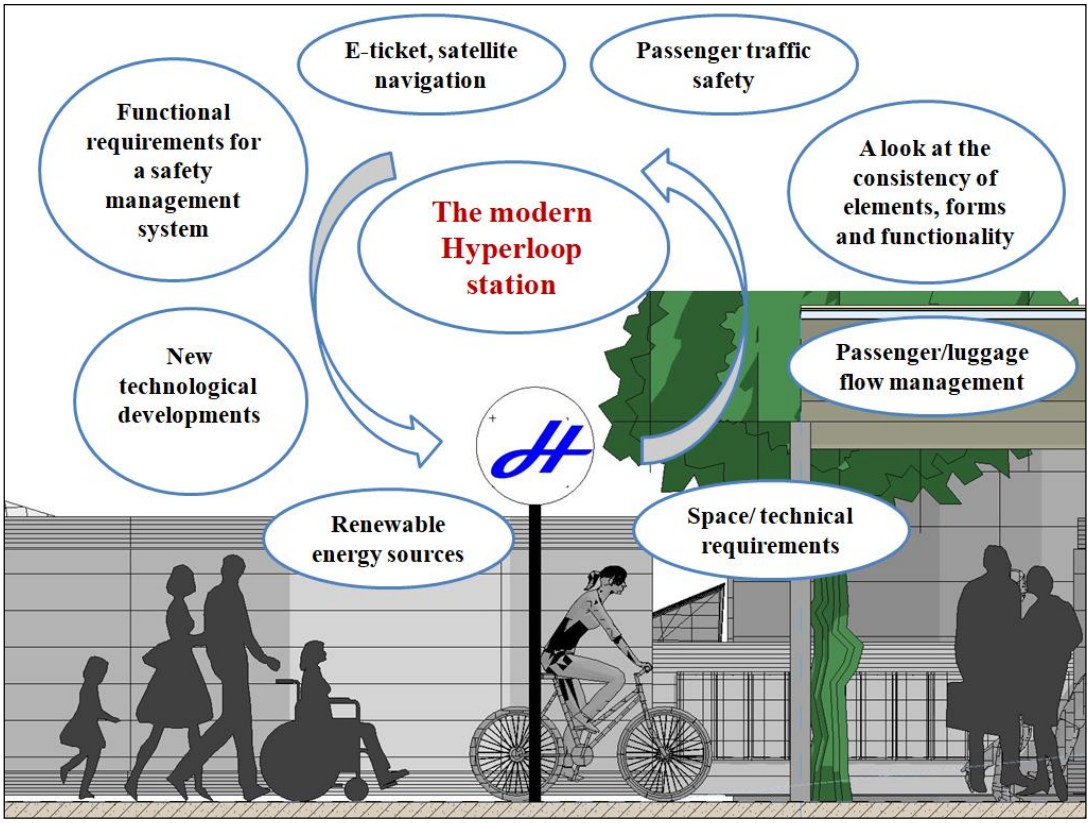

Figure 6. Main aspects to be covered in a Hyperloop station building design.

The system to which this paper refers is a three-tube system where traffic direction is defined for each tube. The middle tube is supposed to serve as the left or the right tube in case one of them is disabled. The main advantage of a three-tube system is the independent work of each tube. Double airlock chambers are designed to make this system capable of operating double-pod trains or to receive two-pod trains, where if the first one gets broken in the tube, the second one pushes it through the tube to the station. Double airlock chambers can also be considered as parts of a safety system which can be extremely useful during renovations or overhauls. It is obvious that double airlock chambers prevent the hyperloop system from stopping when one airlock is broken and one airlock chamber is out-of-order, because, in such a situation, the second airlock chamber is enough to maintain pod flow until the necessary changes in traffic organization are done, i.e., pod traffic is shifted to the middle tube till the broken airlock is fixed.

Airlocks are crucial component parts of a hyperloop station, because they connect the atmospheric pressure zone with a vacuum or low-pressure tube. One option is to place airlock chambers in the station hall where passengers gather at platforms and wait for entering their pod or leaving the pod which has just arrived. Passengers have easy access to pods. Moreover, a pod may be equipped with 4 doors, so that entering/leaving process may be accelerated. Certainly, passengers are obliged to get familiarized to the passenger and luggage transport rules as well as with safety instructions. In this paper another option is propounded, i.e., to locate airlock chambers in the low-pressure zone, so after inflating or removing air, a pod containing passengers can move to the station or to the tube, respectively. Removing air from airlock chambers is a rapid process. An advantage of such a solution is to operate the airlocks in the low-pressure zone.

Figure 7 presents the view on the station at the track level, where passengers board and disembark the capsules, so that the entire multi-story hyperloop station is not in the atmospheric pressure environment. It is like a railway station, so passengers will be surrounded with infrastructure which is familiar to them, such as lifts, escalators, paths to platforms, platforms, etc. Passengers can use escalators, lifts, or stairs to reach the platforms (see Figure 7). The public space of the hyperloop station is fully accessible for passengers with limited mobility and people in wheelchairs. They can use lifts or hoists to get to any platform. The usable area of the hyperloop station should correspond to the nature of passenger traffic flows and meet specific requirements of the safe sending and receiving of pods and capsules. Passenger safety should be ensured according to the existing standards for the station building design. Nevertheless, there is a need to enact separate guidelines for the hyperloop station design, especially the standards on connecting atmospheric pressure zones with low-pressure zones.

Moreover, the station will be equipped with an apparatus and instruments for fire protection and fire detection as well as with fire-fighting equipment stored in fire-protected rooms and available for the station staff at any time.

The capsules will have four doors to make embarkation and disembarkation smooth and fast, so that the capacity of the station can increase. Capsules will depart every 90 s. Behind the outer wall of the station, a technical area with turnouts in both directions is located.

In the project presented in Figure 8, switches connect station platforms (which are in a lower level) with low-pressure zones (where airlocks are located). In result, the throughput capacity of the hyperloop station increases. The main advantage of such design is that both station platforms and the so-called technical zone containing switches are in the atmospheric pressure zone, so technical staff can operate there in the same manner as everywhere else. Moreover, the technical zone may also serve as a safety buffer at the entrance to the airlocks. In the hyperloop system to which this paper refers, right-hand traffic organization is adopted, therefore the pods and capsules should always use the right-handed tunnel in the direction of traffic. In the event of a breakdown of a left-handed or right-handed tunnel, it is possible to shift traffic flow to the middle tunnel. The direction of traffic in the middle tunnel is adapted when necessary.

Airlocks connect the technical zone of the atmospheric pressure environment with low-pressure tunnels 1–3. Airlock doors move in an up-and-down direction and each of them is equipped with a manual opener, so the airlocks can be opened even if the automatic door opener fails. Each airlock chamber is also connected with evacuation roads which are filled with air. After a pod enters the airlock chamber, airlock doors close and air is pumped out. Behind airlocks, an airdock for backup pods is located. Designed double airlock chambers operate in the following way: one of them acts as a main airlock chamber, while another serves as a backup airlock chamber. The main airlock chamber is used for single-pod traffic, while the door of the backup airlock, shared with the main airlock, are constantly open to reduce the wear of the backup airlock as well as to minimize the time of pumping air out (from a single airlock chamber). Moreover, the backup airlock is shared with the tunnel double door to prevent vacuum from permeating to the airlock chambers. The safety system will operate as follows: when the airlock door of the main airlock breaks down, the door of the backup airlock is used automatically, so the situation causes no disturbance to the traffic flow. Another advantage of double-airlock chambers is that service staff can safely carry out technical inspections and repairs. Backup airlock chambers can be used in case of a breakdown to receive a pod which broke down in a tunnel and is being pushed through the tunnel to the airlocks, so that it can be moved to an airdock or a garage. On a daily basis, backup airlock chambers will be used when double-pods operate in the system.

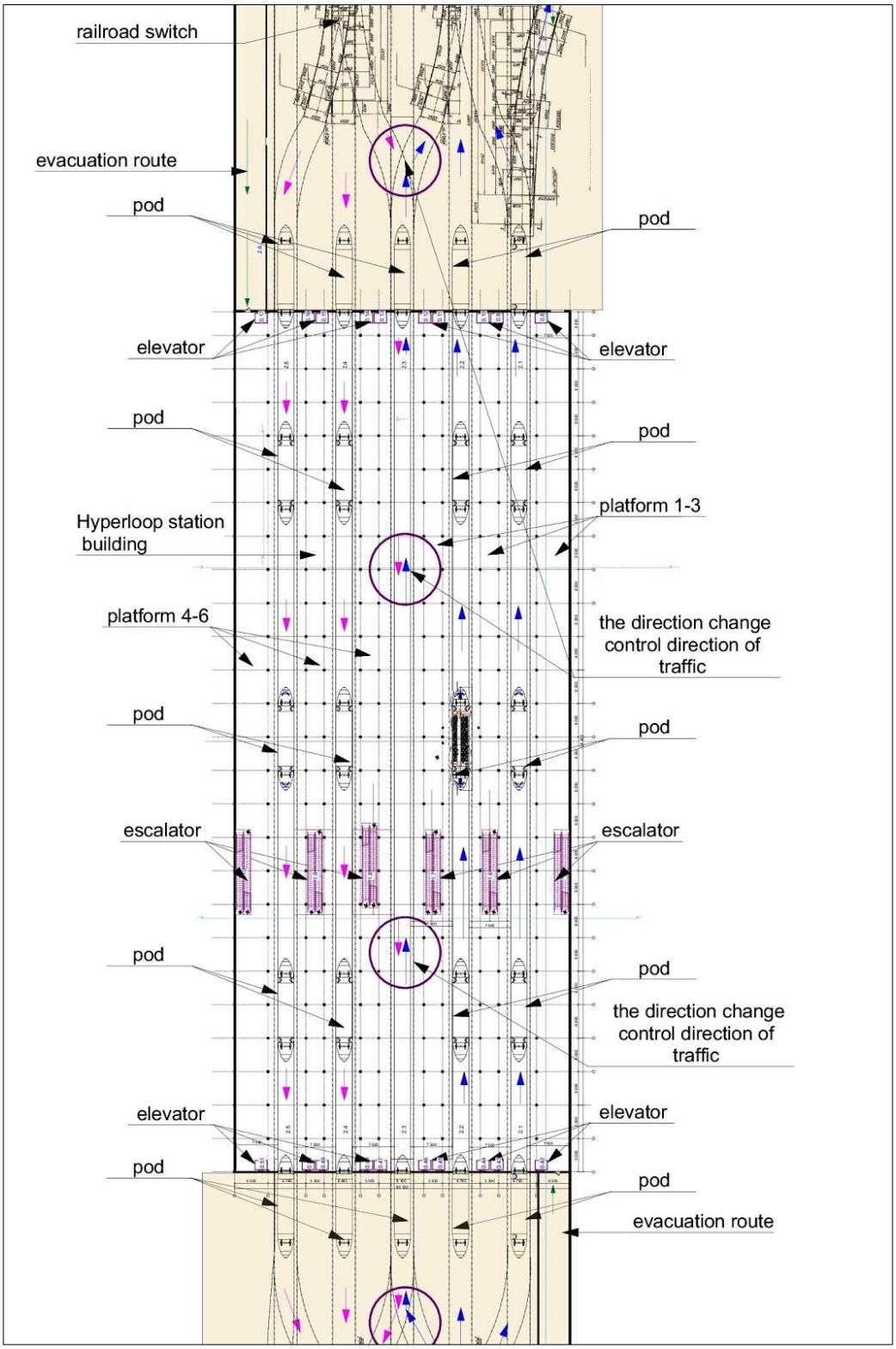

Figure 7. Detailed presentation of turnouts in the technical zone.

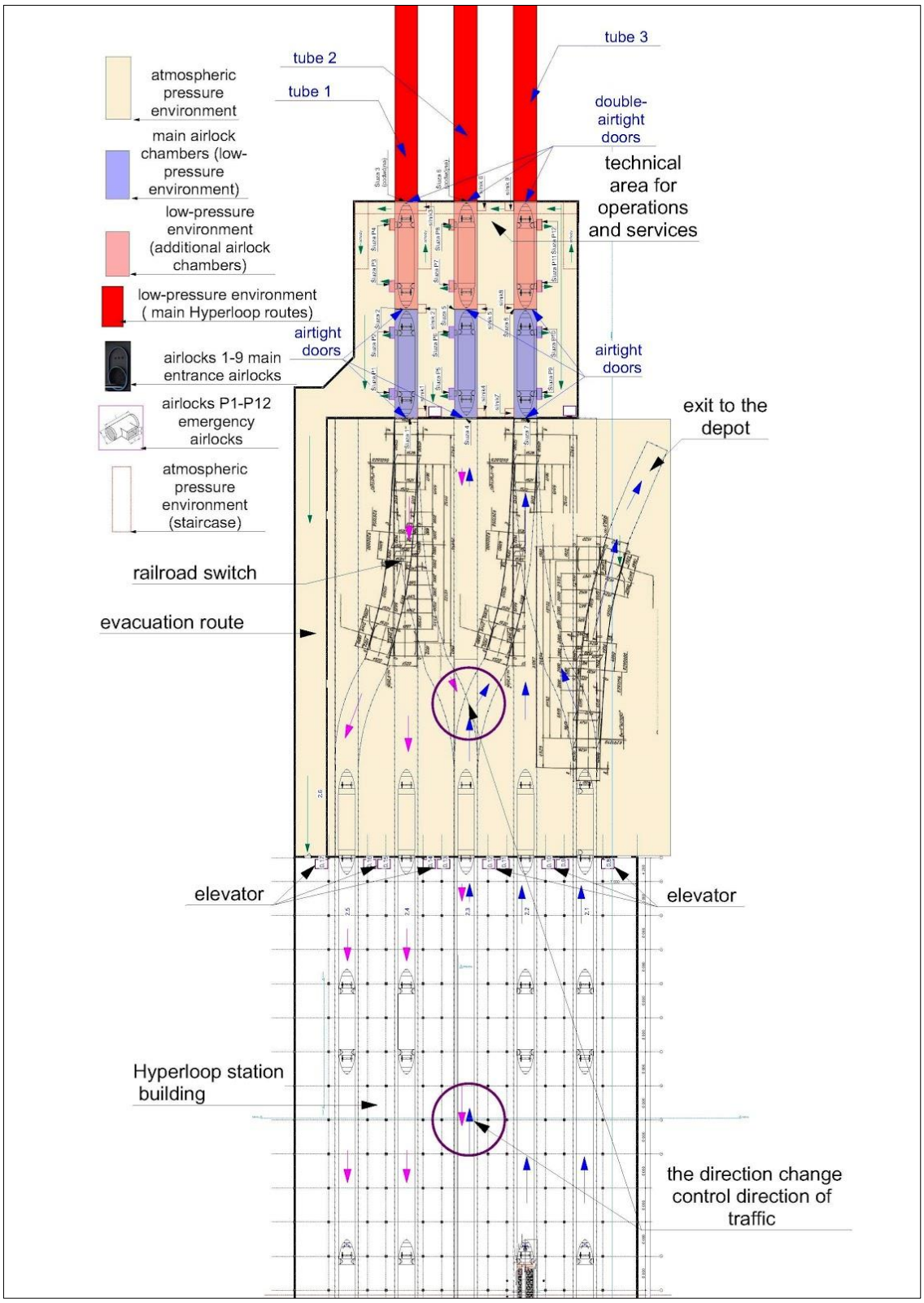

Figure 8. Fragment of turnouts in the technical zone.

When an entrance to the station is blocked, all the pods that are involved in the blockade and trapped in the station must go back to the platforms, to discharge passengers and go to the airdock, so that the system may be unblocked. Evacuation roads serve for passenger evacuation in case

an airlock does not work properly, or as technical zones used by the staff conducting inspections. Moreover, in this concept, evacuation roads lead from a technical zone just towards platforms because the technical zone is filled with air.

Note that in the designed system, passenger safety comes first, however, its weaknesses can be indicated and briefly discussed. The displacement of passengers in the pod going through the low-pressure tunnel can be included among the weaknesses, therefore, the hyperloop pod or capsule is an important part of the passenger safety system. It is obvious that the pod should provide air circulation and temperature regulation in the passenger compartment, but also the pod should be equipped with a reservoir with an additional air supply to be used if the pod is stopped in the low-pressure environment in a tunnel. Each pod has enough air in a tank, so that it can safely reach the emergency sector (see Figure 9). In this three-tunnel concept of the hyperloop system, it was assumed that in case there is any disturbance in a tunnel, the tunnel section where it has happened is automatically identified. From that moment on, the traffic from that tunnel is redirected to the middle-tunnel and the tunnel where a disturbance occurred acts as a technical tunnel until the disturbance is removed. If the broken pod is still able to move, it can reach the nearest evacuation sector where passengers can be evacuated. Otherwise, the pod can be hauled by a technical vehicle.

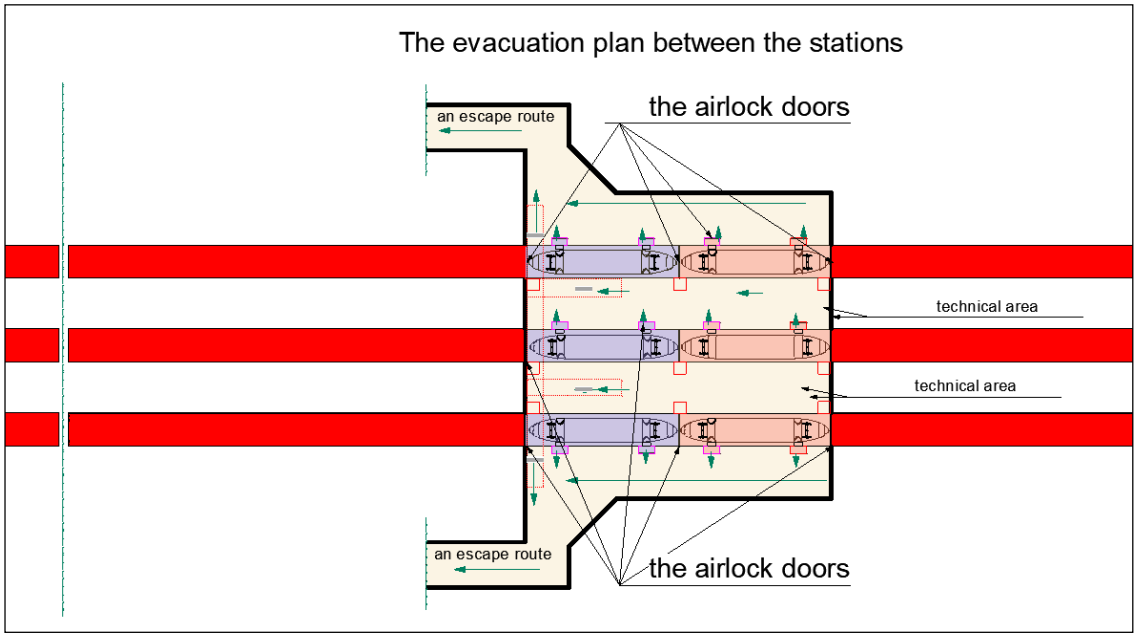

Figure 9. An emergency sector located in the Hyperloop tube.

Another weakness is the risk of the pod becoming unsealed. To prevent such a situation, a triple protection of the pod structure is provided. The prototype of a pod will be carefully tested. To ensure safe evacuation of passengers in case of a pod becoming unsealed in a tube, each of them is equipped with emergency airlocks located in repeatable distances. The airlocks will equalize the pressure in the given tube sector in a very short time, so a dangerous situation for the passenger can be avoided. The pods will move through the tube, keeping a safe distance from each other, which allows them to slow down and stop in case of emergency.

The human factor can also be listed among the weaknesses of the hyperloop system. The rapid acceleration of the pod in the tube affects the condition of the passengers. For this reason, detailed research should be conducted to prevent negative factors from happening or to deal with them. Discussing risk factors natural phenomena like earthquakes should also be mentioned. At every stage of the hyperloop route design research are being conducted, so that the hyperloop tube can be as resistant to natural phenomena as possible. For instance, if the Hyperloop route is elevated as an overground system, appropriate precautionary structures must be designed. Depending on the

construction of the hyperloop transport system (ground, overground or underground) or the chosen technology for moving pods in the tunnel, there are numerous specific aspects which can be considered as weaknesses or strengths and require detailed examination.

Figure 10 illustrates how passengers can enter and leave a pod at a platform of a vactrain station. Note again that public spaces at the hyperloop station are accessible for passengers with disabilities or reduced mobility, thanks to lifts, hoists and escalators which are available at every platform. Therefore, wheelchair users can reach any platform they need. Passenger crossings and paths to parking spaces are easier accessible, thanks to dropped curbs and wide doorways.

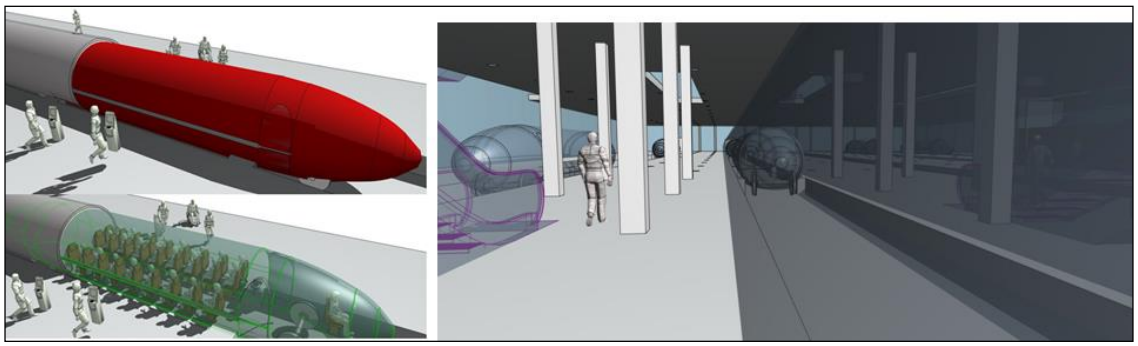

Figure 10. Visualization: how passengers can enter and leave a pod at a platform of a Hyperloop station.

The hyperloop station building contains rooms for people with disabilities, VIP rooms, numerous waiting rooms, service rooms, maintenance rooms, utility rooms, toilets, City Guard stations, business premises, and so forth. Certainly, there are direct paths towards platforms. The main advantage of the proposed hyperloop station building is a multimodal safety management system implemented there. For instance, in this project, tubes are equipped with emergency sectors which are located at a substantial distance one from another, so once damage to tube integrity occurs, airlocks in neighboring emergency sectors will close. The system decides on airlocks to close considering positions and the speed of pods in order to guarantee that all the pods will safely reach emergency sectors. A safety management system will fill the needed part of the tube with air quickly, so the sector between closed airlocks will shortly have atmospheric pressure. In emergency sectors, passengers can be evacuated outside the tube using escape routes, and pods will also be taken out of the tube for technical inspection (see Figure 9). Such a safety management system ensures short repair time; therefore, the hyperloop would not be suspended from operation for a long time. The proposed safety management system results from the assumption that in the technologically advanced transportation system safety comes first.

4.2. Traffic Flow Management Plan, Critical Issues for Safety, and the Reduction of Passenger Transit Time

The hyperloop is an innovative means of transportation, so its proper operations are determined by numerous technological, economic, and operating factors. Disruptions of the hyperloop functioning may result from:

- inappropriate functioning and operations in the station building;
- insufficient maintenance and technical aspects of transport system;
- human factors;
- random events.

The way the station building functions and the kind of operations performed at the station are determined by standards applicable after the station is commissioned. Hence, once an unusual building connected with low-pressure tubes is to be build, additional specific standards of its functioning and operations must be defined. For critical parts of the system, it is advisable to organize a tender in order

to select the best companies to provide maintenance in the shortest time so that the hyperloop system is not disturbed by ongoing maintenance and repair works. The functioning and operations in the hyperloop station building are presented in Figure 11. Traffic flow management is crucial to optimize available capacity of the hyperloop station building and to improve processes subject to daily and seasonal fluctuations. Traffic flow management should be focused on ensuring the safe movement of passengers at the station and through the tube. As a result, the hyperloop transportation system should operate effectively, and the capacity and throughput of the tubes should be in line with passenger travel demand. Other critical issues are potential disruptions in the pods' timetable.

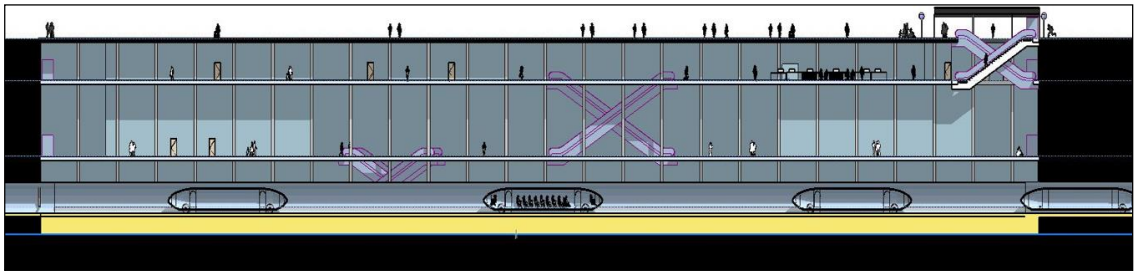

Figure 11. Functioning and operations in the hyperloop station building.

The critical issues related to the maintenance of the hyperloop transport system are during the inspection, some section of the tube is out of service and the pods must be redirected to the middle tube which generates additional operating costs. Moreover, during the hyperloop station lifecycle, a competent technical inspection body may want to inspect the facility in use: commissioning tests, periodic verifications, occasional in-service tests, and checking technical staff certificates and qualifications. During such inspections, some airlocks may be required to be closed and some tube sections may be out of use, which can extend travel time or cause temporary stoppage of a number of pods. Failures may be considered as critical issues, because they may result in stopping the whole transportation system for good.

Another critical issue refers to the human factor, i.e., errors in information flow which may lead to stoppage of pods or to collisions. This may result in decreased throughput of the hyperloop transport system and increased operating costs. Extended travel time may reduce the robustness of this means of transportation and, in consequence, lower the level of passenger confidence.

Random events can also be considered critical issues that are characteristic of a hyperloop station. Random events include terrorist attacks, epidemics (including pandemics of infectious diseases), or extraordinary safety conditions when the system operates with low-pressure tubes. Random events may significantly influence the effectiveness and robustness of vactrains. Therefore, it is necessary to develop and maintain simulation models of the traffic in the system, so that traffic flows and passenger behavior can be observed, passenger transportation needs can be identified, and the optimal hyperloop speed can be determined.

When critical issues in the abovementioned order are analyzed, they can be controlled at every stage of the decision-making process. Therefore, it is so important to create a travel simulation model representing the real movement of passengers, their needs and hyperloop travel times. This approach allows to determine critical points and their impact on each stage of the decision-making process.

5. Conclusions

This paper studies the planned mega transport hub, the Solidarity Transport Hub Poland, as a potential location of a hyperloop station. The analysis of the main assumptions of the STH project proves that this location is in line with worldwide trends in hyperloop route planning as well as with the Polish national strategy for advanced transportation systems.

Advanced technology of low-pressure high-speed trains may be a game changer for transportation systems because it combines the advantages of railways and aviation. The hyperloop seems to be perfect for medium-distance travels (ca. 200–500 km) as a supplementary means of transportation. In Europe, low-pressure high-speed trains may improve travels between the main cities. The design and location of the hyperloop station remain open questions. Multifaceted studies recommend designing the hyperloop routes with stops (intermediate or final) at airports and integrate the vactrain stations with airport facilities, so that transport hubs can be created.

In Poland, the planned first vactrain route has an intermediate and is supposed to stop in a planned mega transport hub, the Solidarity Transport Hub Poland. In the future, hyperloop routes are supposed to connect STH with other Polish cities. Therefore, this paper presents a concept of a hyperloop station, keeping its potential integration with the STH in mind. The final project of the STH has not yet been chosen, so the research was conducted without any reference point, i.e., the foreseen location of the vacuum train station in the STH. For this reason, our project on the Hyperloop station is an underground station, at the moment, that can be located it in any part of the STH. This study was safety-oriented in terms of a number and locations of airlocks and evacuation roads. The issue was studied thoroughly, as connecting the station building and low-pressure tubes is crucial for the functioning of the station and such a solution has not been employed in a massive transit system ever before. Another focus of the project was ensuring accessibility and coping with various passengers' needs and limitations. At the same time, we had to make sure the passenger traffic flows fast and smoothly, so that the station is not a bottleneck in a massive system, which the Hyperloop aspires to be in the future.

This study shows that obtaining the desired coherence of processes at the hyperloop transportation system requires dealing with numerous critical issues—some of them are well known, some of them can be foreseen, but there are many unidentified issues, and it is necessary to conduct further detailed research to reveal them all, assess the risks, and find adequate solutions. For instance, the safety management system described in this paper resulted from a multi-perspective analysis and discussions in interdisciplinary teams of experts. Safety issues are crucial for the hyperloop system, because the fear of low-pressure tubes may prevent passengers from choosing this means of transportation. Further research of the safety management system will include the computer simulation of passenger flows, laboratory tests of the infrastructure, and on-site tests at a hyperloop pilot route.

The main contribution of this paper is a concept of an underground station for a three-tube low-pressure high-speed train system with an extensive analysis of safety issues and an original project of a safety management system that includes double-airlock chambers and evacuation roads. The project of the hyperloop station building and facilities is designed for low-pressure high-speed train technology developed in Poland, however, all the findings are generic and may be useful for any hyperloop project.

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