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KEY POINTS OF THE MANAGEMENT SYSTEM FOR THE SAFETY OF PASSENGERS TRAVELLING WITH LOW-PRESSURE TRAINS

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INTRODUCTION

Hyperloop (HL) technology has recently reached a milestone when Virgin Hyperloop successfully carried out tests of their ultra-speed transportation system with human passengers, in other words for the first time, two people rode a hyperloop pod through a nearly airless tube at 160 kmph, what makes travelling through vacuum tubes at speeds of up to 1,223 kmph more and more realistic as the fifth means of transportation (Hawkins, 2020).

The HL transport technology is claimed to provide superior performances to high-speed rail and airborne transportation due to enormous reduction of travel time, transport costs, energy consumption, and great increase of transport safety (van Goeverden *et al.*, 2018). Nowadays, research on hyperloop technology are conducted by several research groups and companies all over the world, but the general idea is the same: to move passengers and goods placed safely capsules through a low-pressure tube with the speed ca. 1200 kmph, so than air resistance can be reduced and requirements of sustainable transportation can be met (Musk, 2013; Błażejczyk and Różycka, 2018; Fajczak-Kowalska and Kowalska, 2018; Gkoumas and Christou, 2020; Kim, 2018; Mielczarek and Foljanty, 2019; Ross, 2016; Jeker, 2019; Zhou, 2018; Majchrzak *et al.*, 2018). The main directions of hitherto studies on hyperloop technology have concentrated on technological aspects of propulsion, e.g. the electromagnetic levitation (Soni *et al.*, 2019; Pradhan and Katyayan, 2018; Abdelrahman *et al.*, 2018; Tudor and Paolone, 2019; Lafoz *et al.*, 2020), the dynamics of the HL capsules and low-pressure tubes (Rajendran and Harper, 2020; Niu *et al.*, 2020a; Nowacki *et al.*, 2019; Belova and Vulf, 2016) the HL infrastructure and their resistance to natural catastrophes (Ahmadi *et al.*, 2020; Alexander and Kashani, 2018; Taylor *et al.*, 2016; Heaton, 2017) environmental aspects of the HL technology including energy consumption and utilization of renewable energy sources (Janić, 2020; Nowacki *et al.*, 2019; Sayeed *et al.*, 2018-2018; Lafoz *et al.*, 2020; Roswall *et al.*, 2018; Rajendran and Harper, 2020) as well as costs and benefits associated with operational, economic,

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social, and environmental performance of the HL (Janić, 2020; Almujibah *et al.*, 2020; van Goeverden *et al.*, 2018; Rajendran and Harper, 2020). As the deployment of the HL technology gets more and more real, the design of hyperloop station and passenger safety management issues need systematical exploration, however existing studies on these subjects are scarce (Dudnikov, 2019; Taylor *et al*., 2016; Covell, 2017; Stryhunivska *et al*., 2020; van Goeverden *et al*., 2018; Rajendran and Harper, 2020). This work aims at filling in this gap by studying critical safety issues and propounding a way of dealing with one of them, i.e. the design of an emergency node with evacuation roads

This paper presents an analysis of hyperloop technology in terms of ensuring passenger safety when travelling in a low-pressure rail tunnel (KNC). Obtaining the desired consistency of processes in the hyperloop transport system requires solving many critical problems – some of them are well-known, some are predictable, but there are also new, unidentified ones. Therefore, a detailed analysis of the passenger safety system is necessary to identify all critical points, assess the risk and find an appropriate way to deal with it. The scope of research presented in this paper includes the design of elements of the safety management system and infrastructure that will ensure the safety of passengers at the station with atmospheric pressure, despite the station's interaction with low-pressure tubes during entry and exit of the capsules. It can also be used to evacuate passengers from low-pressure tubes in an emergency situation. The paper focuses on defining critical points of passenger safety as an integral part of the hyperloop transport system. The most important issue is to ensure the safety of passengers in the low-pressure zone, also called vacuum, which is deadly for people. The fear of negative pressure may have a significant impact on the reluctance of passengers to use this means of transport despite its obvious advantages. Therefore, it is extremely important to equip hyperloop stations and tunnels with such safety management systems which ensure reliability of operations and proper evacuation in case of failure. The same problem concerns a hypothetical situation, leakage of a hermetic capsule.

The main advantage of hyperloop station is an integrated safety system understood as a multifunctional platform for managing technical security systems. Ensuring the safety of interaction between these two zones at the high frequency of capsules is an independent vast research area. The HL station differs from both the traditional rail station and the airport mainly due to the interaction between the atmospheric pressure zone and low-pressure tunnels. However, this structure must meet the basic criteria for station facilities, i.e. (1) adaptation to the characteristics of transport means, (2) passenger service, (3) architectural and urban planning guidelines as well as (4) economy of use (Mohajeri and Amin, 2010; Stoilova and Nikolova, 2017).

The authors' original achievement is the identification of critical points of passenger safety during their stay in the station area and during their journey through a low-pressure tunnel, as well as the design of a double airlock that can be used in the hyperloop tunnel at repeatable intervals with the aim of evacuating passengers to the atmospheric pressure zone. The designed solution allows to eliminate one of the significant weaknesses of the transport system using low-pressure rail.

The remainder of this paper is structured as follows. The next section briefly presents a selection of critical safety points of hyperloop system and surveys safety aspects addressed by hyperloop research groups and measures propounded to deal with these issues. The subsequent section describes a concept an evacuation node to be located at a hyperloop station building and in emergency sectors in low-pressure tubes, so that in case of emergency passenger can be safely evacuated to atmospheric pressure environment. In the last section, conclusions are drawn and recommendations for further research are formulated.

SAFETY MANAGEMENT ISSUES IN THE HYPERLOOP TRANSPORT SYSTEM

The innovation of hyperloop technology consists in the use of low-pressure tunnels to transport passengers and goods at ultra-high speeds. This solution opens new aspects of ensuring passenger, goods and infrastructure safety not only due to the use of vacuum environment, but also in terms of functioning of this transport means in urban and non-urbanized environment – its impact on the environment and threats caused by the environment. Among the risk factors in the transport system, ultra-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 (Almujibah et al., 2020; Oh et al., 2019; Opgenoord and Caplan, 2018; Niu et al., 2020; Santangelo, 2018). In addition, it is important to take into account the fact that the ultra-high speeds developed by hyperloop require automatic control, thus the level of complexity of human-machine interactions is high, making it necessary to develop new models of accidents and disasters in KNC traffic, as well as methods, tools and techniques for risk assessment and management (Gkoumas and Christou, 2020).

Above all, the development of transport technology based on low-pressure rail system forces – as in space technologies – to study the impact of vacuum on the human body, which is particularly important in emergency situations. Due to the expected implementation of hyperloop as means of transport, a large group of people may be subjected to the influence of vacuum, e.g. in case of a capsule failure in the low-pressure zone. Persons of different ages should be taken into account: infants and children, the elderly and persons of different health condition. This significantly broadens the scope of research on the influence of vacuum environment, as so far it has focused on a homogeneous group of astronauts (Jia et al., 2018).

Due to the vacuum environment in hyperloop tunnels, the research should cover the issue of decompression, i.e., unplanned pressure drop in a sealed system – a hermetic transport capsule. Most often, sudden decompression is the result of human error, equipment failure or impact, and in the KNC system, it may occur in tunnels or airlocks at tunnel exits to station platforms. The speed and violence of decompression is influenced by the size of object, as well as the pressure difference between the inside and outside of object and the size of leakage hole. As a result of decompression, serious body injuries may occur, such as hypoxia, barotrauma or decompression (caisson) disease. Early warning and pressure monitoring systems inside the capsule are part of the safety management system for monitoring and reacting in case of occurrence, which is crucial in case of slow (gradual) decompression that is usually unnoticed by the crew and passengers. This issue should also be taken into account in the design and construction of capsules, which should be equipped with individual life-saving devices, such as oxygen masks for passengers, as well as appropriately designed safety exits (Li et al., 2019; van Goeverden et al., 2018).

The research issue related to the target speed range above 1200 kmph is the effect of overload on potential passengers, reaction to external forces other than gravity. The human body is not adapted to withstand high overloads. Immediate and dynamic change in blood vessels – the outflow or inflow of blood causes a drastic increase in organ pressure. In extreme cases, they may cause life-threatening conditions. It is possible to operate and generate balancing forces that can relieve the negative effects of overload on the human body (Jia et al., 2018; Janzen, 2017).

Hyperloop's architectural solutions and their interaction with the capsules moving inside the tubes, such as the construction of overground tunnels, on flyovers or in underground tunnels, are the subject of detailed research. The safety management system also takes into account the ways of evacuating passengers from the tunnels in case of emergency. The frequency and timing of the consequences of capsules, as well as the way they leave the starting station and arrive at the destination station in order to prevent collisions (i.e. to guarantee safe capsule deceleration) in case of a failure of the speed control system were also investigated. The way to ensure the safe vehicle travel at the station is to correctly guide the capsules to the platforms by means of crossovers and redirect the capsules not stopping at the station through a tunnel bypassing the station, thus avoiding unnecessary movement of the capsules through the atmospheric pressure zone (Dudnikov, 2018; Janzen, 2017; Ahmadi et al., 2020; Alexander and Kashani, 2018). At the operational level, the element of security system is to ensure the smooth flow of passengers, especially the processes of security control, entry and exit of the capsules and baggage handling (Li et al., 2019).

ANALYSIS OF PASSENGER EVACUATION HAZARDS

Efficient, comfortable and willingly used means of transport by passengers is a real opportunity to reduce the nuisance of inter-city travel. This paper presents the new generation of hyperloop transport system which is an innovative technical solution. However, new transport solutions and travel models must take into account the following factors:

- moving at high speed, meeting the requirements of sustainable development,

- comfort and safety of passengers during the journey,
- relatively low ticket prices,
- possibility of connecting communication nodes,
- flexibility in passenger travel planning,
- modernity and reliability in passenger transport.

In addition, the new transport solutions define the rules that passengers are required to become acquainted with the conditions of passenger transport and their luggage, to become familiar with the conditions in case of evacuation. The main advantage of the modern hyperloop station is the integrated security system as a multifunctional platform for managing technical security systems. When the integrity of tunnel is damaged, the airlocks in adjacent sections will be closed, at distances that guarantee safe stopping of vehicles. Additionally, they will be supported by systems of emergency airlocks located in the tube at repeatable distances in evacuation nodes. Planning an evacuation node requires estimating the load of planned hyperloop transport system in variant terms. The vehicle traffic intensity determines the possibility of planning evacuation nodes on appropriate sections of tracks. Moreover, the development perspectives of hyperloop transport system must be taken into account, which leads to an increase in annual passenger capacity and has an impact on the design of the number of evacuation nodes and the determination of potential underground space development sites. Hyperloop safety systems will allow to equalize pressure in tubes of the relevant section in a very short time. Moreover, each section will have airlocks with the possibility to evacuate passengers outside and the vehicle will be directed to technical inspection. Such a solution will allow for quick repairs and quick restoration of traffic.

The evacuation node is located in the atmospheric pressure environment (Fig. 1). Three low-pressure tubes are arranged in such a way as to enable the evacuation of passengers from each tube. The middle tube is used as a technical tube and the other two are the main tubes in which trains move in opposite directions. In case of failure in one of the main tubes, vehicle traffic will be redirected to the technical center tube in order to remove the failure in the main tube. If the failure concerns a vehicle that will be blocked in one of the main tubes, the technical vehicle will redirect the emergency vehicle to the nearest evacuation node or return to the nearest hyperloop station. In such an efficient way, the hyperloop transport system will not be disturbed. Depending on the type of vehicle used (single or double), passengers will be evacuated through the S1-S6 airlock chamber. Each of the above mentioned airlock chamber has main airlock doors (1-15), closed in case of an emergency or periodical technical check, from which 1-2, 3-4, 5-6, 10-11, 12-13, 14-15 – the are double-airlock doors. Double-airlock doors constitute a double protection. In case of failure of one of the doors, the other door does not allow the passage of vacuum to the airlock chamber and is a guarantee of passenger safety. In addition, tunnels 1-3 are designed to allow the vehicle to stop in case of failure at a designated point of the evacuation node in front of the additional airlock doors (P1-P12).

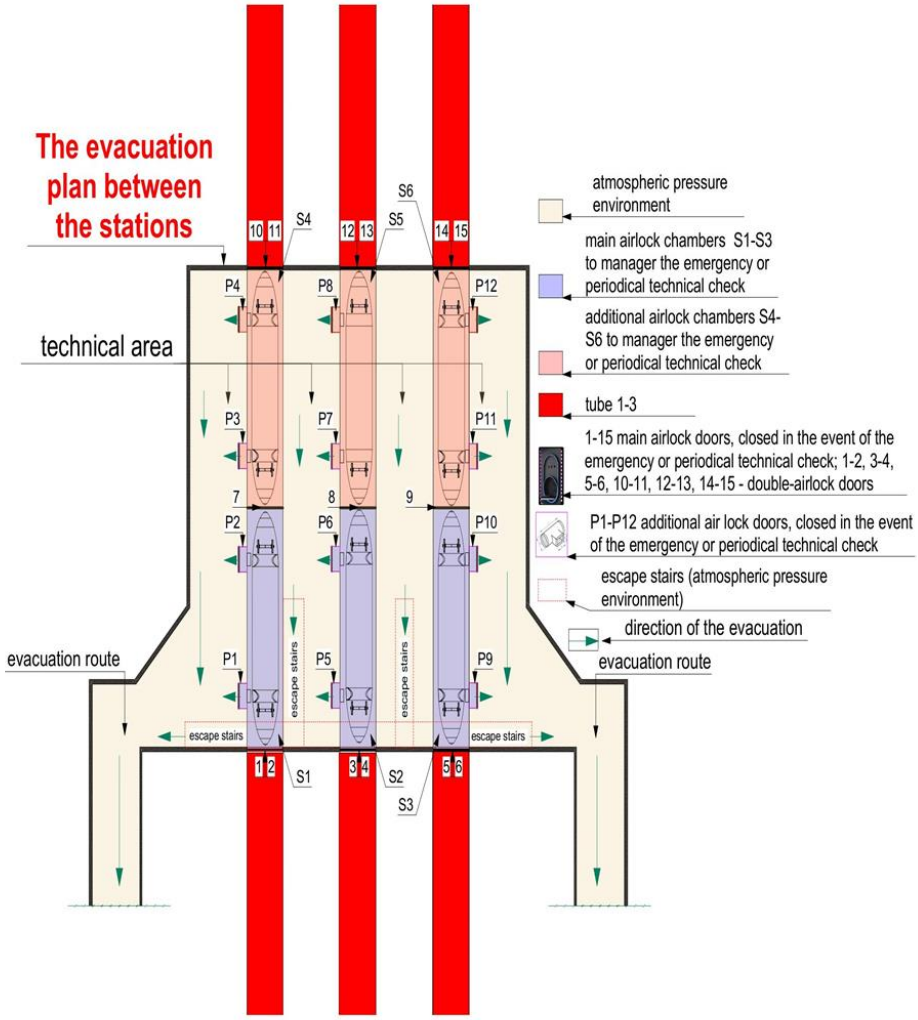

Fig. 1 The evacuation plan to be executed in an emergency section at a hyperloop station building or in a low-pressure tube

Source: (Stryhunivska *et al.*, 2020)

The S1-S6 airlock chamber is used to evacuate passengers through additional airlock doors (P1-P12) in the evacuation route. The Figure 1, shows the direction of evacuation. Next to the evacuation route there is a technical zone designed to handle the equipment. For the transition from one technical zone to another, stairs have been designed which also function as evacuation stairs.

It should be taken into account that every threat and discomfort to passengers needs to be carefully analysed in order to find an effective solution. More important examples are given below:

- Lack of driving comfort – due to the speed of capsule (accelerating, braking, speeding up, sudden stopping), passengers should probably stay seated in their seats throughout the journey;
- Closed, unable to leave the capsule – a claustrophobic problem. Therefore, the passengers' behaviour and mental predispositions require detailed research;
- Sudden changes in speed – susceptibility of the passenger's body to relatively high accelerations and decelerations related to speeding up and braking the capsule in the tube;

- Detailed personal inspection – necessary before entering the capsules, supposedly like at airports. The issue of baggage transport, which could be carried by hand or in special, separate capsules, dedicated to the transport of such shipments, remains open.

Advantages of the transport system:

- Speed,
- Mobility,
- Full environmental compatibility,
- Possibility to transport cars,
- No resistance to Movement.

CONCLUSIONS

This paper presents the issues of security management in the KNC transport system. Security management requires the determination of methods in order to identify the availability of security measures as well as to deal with the different passengers' needs and limitations. Ensuring high security standards in the fifth transport mean will allow to dispel the passengers' fears of hyperloop travel. On the other hand, it is necessary to guarantee smooth passenger traffic within the station to ensure that the station is not a bottleneck in the KNC network.

It should be emphasized that the success of hyperloop's transport system depends on the chosen technology of capsule movement. The issues of passenger safety must be taken into account in the design and operation on each track section. The aim of the KNC project is to create a transport system that will be technically reliable. However, the specificity of hyperloop technology causes that safety issues constitute a significant research area which often requires exploratory research as the innovation of this technology exceeds the safety management problems occurring in existing transport networks. Some elements of security management find common ground with space research. However, they need to be extended and adapted to mass transport conditions.

The solution presented in this paper is an element of the infrastructure security system and was designed due to specific features of the hyperloop system – low-pressure zones in which passengers travel – and general requirements of the security management system. It is a universal solution that can be applied both in the station area (airlock at the transition from tunnel to platform) and in low-pressure tunnels in rhythmically repeating evacuation nodes. As the level of technological readiness increases, the designed solution requires pilot tests in the KNC tunnel prototype.

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Abstract.
Due to the innovation of transport means based on hyperloop technology, the correctness of its functioning should be investigated in relation to many technical, economic and operational factors. This paper presents an analysis of the hyperloop technology from the point of view of ensuring safety of passengers while travelling in a low-pressure rail tunnel. The main subject of research was the design of hyperloop station infrastructure and the safety management system that will ensure the safety of passengers at the station in the sphere of atmospheric pressure, despite the station's interaction with low-pressure tubes during entry and exit of the capsules. The safety management system also includes evacuation of passengers from low-pressure tubes in an emergency situation. The paper reviews the key issues of passenger safety in the hyperloop transport system, which are the source of justified and unfounded people' fear of using this transport means despite its obvious advantages. The authors' original achievement is the identification of critical points of passenger safety during their stay in the station area and during their journey through a low-pressure tunnel, as well as the design of a double airlock that can be used in the hyperloop tunnel at repeatable intervals with the aim of evacuating passengers to the atmospheric pressure zone. The designed solution allows to eliminate one of the significant weaknesses of the transport system using low-pressure rail.

Keywords: Hyperloop, low-pressure ultra-speed trains, safety management, vacuum tube ultra-speed train, vactrain