SAFETY CHALLENGES IN AN UNDERGROUND HYPERLOOP SYSTEM: A PRELIMINARY INVESTIGATION

[1]Matteo Pachera, [2]Maarten Vanneste, [2]Thijs Verrecas, [3]Bartek Kulig
[1]Sweco, BE
[2]Denys, BE
[3]Hard-T, NL

DOI 10.3217/978-3-85125-996-4-20 (CC BY-NC 4.0)

ABSTRACT

A new link between the train station and the airport of Rotterdam in the Netherlands is under study to increase the passengers' capacity and reduce travel time. One of the proposed solutions is an hyperloop tunnel that travels under the city for about 2 km. This article provides an overview about the safety challenges of an underground hyperloop system. In case of fire on board or sudden loss of cabin pressure, tenability conditions deteriorate quickly due to the small size of the vehicle. The preferred option is to travel to the next station and evacuate passengers from there before they become incapacitated. In case two stations are too far apart, additional evacuation routes are required: through the tunnel or in separate evacuation stations. In the first case the tunnel should be equipped with ventilation (for pressurization and smoke confinement) and evacuation routes. In the second case smaller stations are necessary. Alternatively, additional safety measures can be installed on board (water suppression and oxygen masks) to increase the time passengers can stay in the vehicle. The integration of the different safety measures should be further investigated following the development of the project and of the hyperloop technology.

Keywords: Hyperloop, evacuation, high-speed, vacuum.

1. INTRODUCTION

The hyperloop concept was first described by Elon Musk in a white paper in August 2013 [1]. This system is made of a capsule traveling at high speed in a vacuum tube and it was proposed as a cost-effective alternative to high speed rail and aviation [2][3]. Several routes are currently under-study [4] and a test rig was inaugurated at the European Hyperloop Center in 2023 [5].

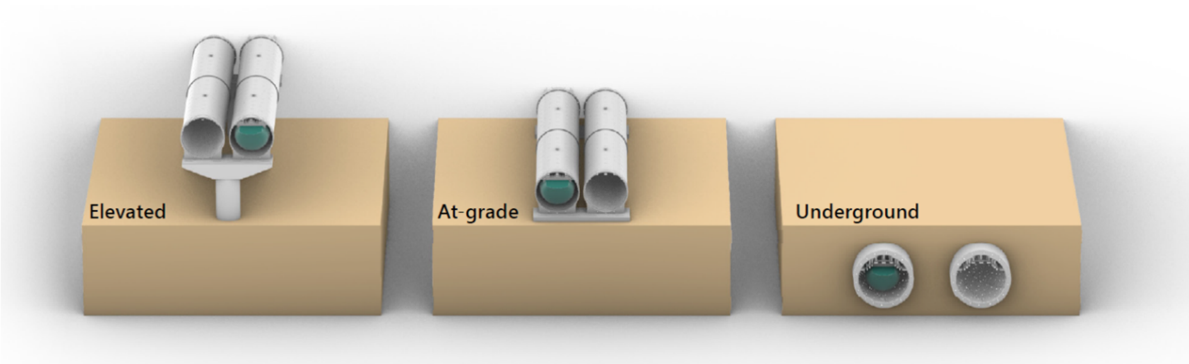

Figure 1: Different tube's configurations

Different configurations for the tubes have been proposed, both above ground and underground. For above ground configurations, each section is separated from the others with airlocks every 500 m. In case of emergency a section is isolated by closing the airlocks and it is pressurized, so passengers can evacuate via the tube. This solution is not applicable to underground configurations, which will be later addressed in this article. Hyperloop's safety has been already investigated in few publications [6][7][8] mostly with focus on the safety systems available on the vehicle. Alternative standards applicable for metro systems could be also applied to hyperloop [9][10], however their solutions can't be implemented directly.

2. SAFETY ISSUES IN HYPERLOOP TUNNELS

A hyperloop system shares some of safety issues of aircrafts and metro systems. The vehicle travels at very low pressures (near vacuum) to limit friction losses and allow higher cruise speed, like a plane. This environment is created with vacuum pumps that remove most of the air from the tube to a pressure of 100 Pa, or 0.1% of atmospheric pressure. The vehicle however travels underground in a closed structure (the tunnel) as a metro train.

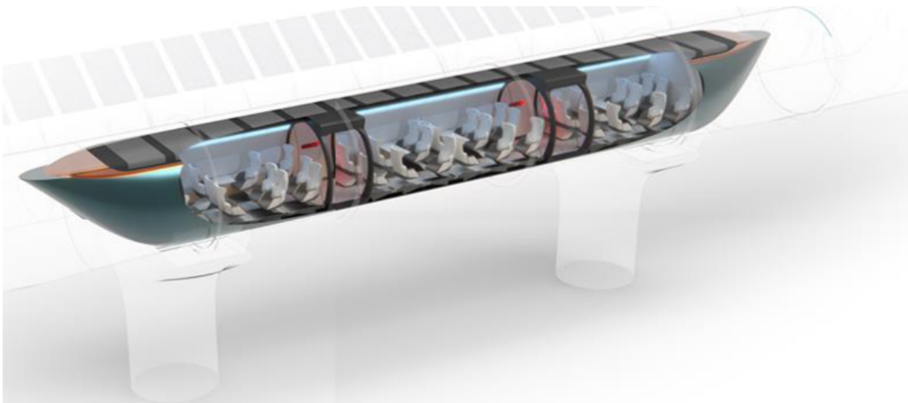

Figure 2: Schematic view of the hyperloop vehicle.

In case of an accident the system must face critical conditions, both related to the underground environment and to the low pressure. The main threats for passengers' life safety are:

- Fire on board: passengers are exposed to heat and toxic smoke.
- Loss of pressure on board: passengers are exposed to low pressure and low levels of oxygen.

In case of fire on board passengers can become incapacitated by the effect of smoke's toxicity and high heat. This is especially relevant due to the small size of the vehicles. The vehicle under study is 24 m long with an outer diameter of 2.5 m [11], Figure 2. The total capacity of the vehicle is 40 seats. Such a vehicle is sealed to keep ambient pressure inside, therefore in case of fire the vehicle can quickly fill with smoke. Based on a preliminary analysis with a luggage fire on board, (medium ground fire with peak HRR of 0.5 MW after 103 s) the time to incapacitation is calculated using FED and FED_{th} [12]. FED reaches a value of 0.3 at 2 m high after 430 s and at 1 m high (assuming passengers are seat) after 450 s. FED_{th} reaches a value of 0.3 at 2 m high after 155 s and at 1 m high (assuming passengers are seat) after 180 s. These times give an idea of the available time to evacuate passengers, about 2-3 minutes, before they become incapacitated and unable to self-evacuate.

In case of loss of pressure passengers can be incapacitated due to low oxygen concentrations, critical hypoxia. These conditions are achieved when the pressure reaches 50% of the initial pressure [13]. The time required to reach this limit value is function of the size of the leakage and the volume of the vehicle (175 m^3). For normal leakages there is no risk of depressurization of the vehicle, however in case of accidents (collision with objects, structural defect) the pressure can drop faster due to larger leakages, Figure 3.

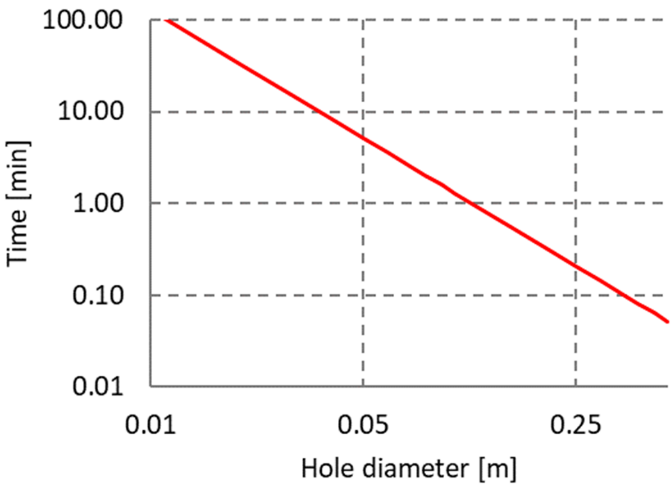

Figure 3: Time to critical pressure as function of the hole size

Based on the analyses above the time to reach critical conditions inside the vehicle can be short in case of fire, therefore the passengers should be promptly evacuated. Different approaches are proposed for passengers' evacuation:

- Evacuation in the station
- Evacuation in the tunnel
- Evacuation in an emergency station

2.1. Stations

In in case of detection of smoke or low pressure on board, the vehicle must travel to the next station to evacuate the passengers into the station. Once the vehicle arrives at the station, it passes through an airdock, where the pressure is reset from the tunnel pressure level to the atmospheric level. Then the vehicle enters the station where passengers can quickly evacuate using 6 emergency doors (4 embarking and 2 emergency doors). The total time to leave the vehicle is around 10-20 s for 40 passengers using 5 out of 6 exits in case of emergency. The different phases of the evacuation process are described in Table 1.

In case the fire is not detected or not detected yet the vehicle arrives to the station in a similar way, but the breaking, pressurization and debarking operations are slower (not in emergency mode).

Figure 4: Example of a vehicle in a station

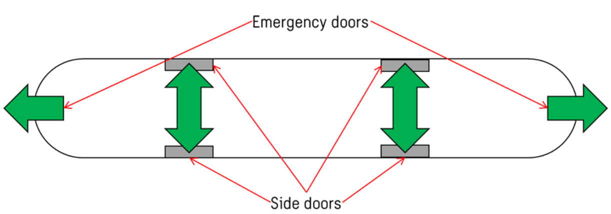

Figure 5: Evacuation scheme from the vehicle

Table 1: Evacuation phases in a station

	Vehicle	Operator	Station	Passengers
↓ Timeline	Accident detection			
		Accident verification		
		Start of station emergency procedure		
	Vehicle reaches the station		Activation of the emergency procedures in the station	
			Pressurization of the airdocks	
	Opening of the emergency doors of the vehicle			
				Evacuation from the vehicle into the station

In case of long routes, the longest delay before the evacuation starts is the travel time required to reach the station. A vehicle travels at 700 km/h at cruise speed and in case of emergency it can break with a deceleration of 0.8 g. This implies that the vehicle requires about 50 s to stop and given the limited time for incapacitation, the total time before doors open should not exceed 2 minutes. Therefore, the vehicle can drive at full speed for about 60 s before reaching a new station, which leads to a travel range of about 11.7 km. This value is only indicative because of the uncertainty about the possible fire scenarios and operational speed of the vehicle. In this scenario it is also assumed that once the doors are open the ventilation is activated to dilute and cool the smoke (as the fire is still relatively small), so passengers are not in life danger anymore. If additional time is required to emergency procedures, pressurization and evacuation procedures, the travel range is further limited. In case the travel time exceeds the time before passengers are incapacitated alternative solutions must be implemented to guarantee an acceptable safety level.

2.2. Ventilation in the tunnel

In case the vehicle is unable to travel to the next station because the travel distance is too long, or the vehicle is damaged, the passengers can leave the train and evacuate through the tunnel. The tunnel should be then equipped with ventilation system to reset the pressure and to confine the smoke with a push-pull approach. The ventilation system should be designed to pressurize the tunnel quickly (less than 50 s) and to confine the smoke only on one side of the vehicle, Table 2. Additional emergency exits and evacuation routes should be added to the tunnel sections to allow a safe evacuation. The distance between doors should be estimated based on the time required by passengers to reach the door without risk of incapacitation.

Table 2: Emergency procedures in tunnel

	Vehicle	Operator	Tunnel	Passengers
↓ Timeline	Accident detection			
		Accident verification		
		Start of tunnel emergency procedure		
	Vehicle comes to halt		Pressurization of the tunnel via ventilation	
	Opening of the emergency doors of the vehicle		Switch to longitudinal ventilation	
				Evacuation from the vehicle into the tunnel and towards emergency exits

This evacuation strategy allows for the maximum flexibility because the vehicle can stop anywhere in the tunnel, and it is less affected by the reliability of the vehicle. However, this solution requires additional evacuation corridors, evacuation shafts and ventilation shafts. These additional installations create new leakage paths to the tunnels, increasing the extraction rate for the vacuum pumps.

2.3. Evacuation stations along the tunnel

An alternative solution to evacuation in tunnel is the creation of additional evacuation stations that can be installed in long routes where the travel time is longer than the time to incapacitation. The evacuation station is like a normal station, there is a pressurization zone and after that the passengers can leave the train using all doors, Table 3. The evacuation station can be equipped with ventilation system to confine the smoke and guarantee a tenable environment for passengers once out of the vehicle.

Table 3: Evacuation phases in an evacuation station

	Vehicle	Operator	Evacuation station	Passengers
↓ Timeline	Accident detection			
		Accident verification		
		Start of station emergency procedure		
	Vehicle reaches the evacuation station		Activation of the emergency procedures in the evacuation station	
			Pressurization of the airdocks	
	Opening of the emergency doors of the vehicle			
				Evacuation from the vehicle into the station

As seen above these stations can be placed at regular intervals (~11.7 km), but this solution requires a higher reliability for the traction system of the vehicle.

2.4. Additional safety systems on board

The three solutions proposed above try to minimize the time required to leave the vehicle. An alternative approach is to increase the time that passengers can stay in the vehicle. Different safety systems can be installed on board of the vehicle to mitigate a fire or a sudden loss of cabin pressure.

- Active water suppression system
- Additional oxygen masks

The presence of a water suppression system on board can prevent the development of small fires into larger one. In case the fire size is limited or suppressed the smoke temperature can be effectively mitigated and the vehicle can drive longer towards the stations. The vehicles are designed without personnel onboard; therefore, the system should be operated automatically or from remote.

The presence of oxygen masks can also increase the travel range of the vehicle to a station because passengers are not exposed to large quantities of toxic gasses in case of fire or low oxygen concentrations in case of pressure loss.

3. CONCLUSION AND FUTURE STEPS

This article provides an overview about the safety challenges and possible solutions associated with an underground hyperloop system. Due to the small dimensions of the vehicle a fire on board can lead to untenable conditions in very short time, thus passengers shall leave within 2-3 minutes. Considering the high speed of the vehicle (700 km/h) this can cover long distances in short time and reach the station of destination where passengers can evacuate. However, in case the next station is out of reach, passengers shall evacuate directly in the tunnel or in evacuation stations along the route. These solutions require additional installations, ventilation and evacuation shafts in the tunnel, or the construction of additional small stations.

Alternatively, the tenability conditions inside the vehicle can be improved with the installation of water suppression systems that can confine the fire and limit smoke temperature. Oxygen masks can be also installed in the vehicle (as in airplanes) to mitigate the effects of toxic smoke or hypoxia.

These different solutions can be combined, and they should be further investigated considering their effectiveness, reliability, and financial impact on the project. Further research is also required to understand the possible fire scenarios that could occur and define a standard fire scenario that could be later used for the design of the different safety systems.

4. REFERENCES

[1] E., Musk, "Hyperloop Preliminary Design Study Technical Section", Tesla Hyperloop Alpha (tesla.com)

[2] Hard-T, "Mode comparison", Hyperloop Progress Paper (hardt.global)

[3] Hard-T, "Hyperconnected Europe" Hyperconnected Europe (hardt.global)

[4] Hard-T, "Studies" Studies (hardt.global)

[5] Hyperloop development program, "European Hyperloop Center marks its kick-off in Veendam", European Hyperloop Center marks its kick-off in Veendam — European Hyperloop Center, 2023

[6] TÜV SÜD, "Hyperloop ApplicationGeneric Guideline for Design, Operation and Certifi cation", 2017.

[7] J. J. ter Kuile and M. L. M. Beek, "Safety Framework for the European Hyperloop Network," Delft Hyperloop, Delft, 2020.

[8] Mateu, Jose M., Pablo Martínez Fernández, and Ricardo Insa Franco. "Setting safety foundations in the Hyperloop: A first approach to preliminary hazard analysis and safety assurance system." Safety science 142 (2021): 105366.

[9] NFPA 130, "Standard for Fixed Guideway Transit and Passenger Rail Systems," National Fire Protection Association, 2014.

[10] Gemeente Amsterdam Dienst Infrastructuur, Verkeer en Vervoer , "Amsterdamse Leidraad Integrale Veiligheid ondergrondse tram- en metrosystemen (ALIVs)," Amsterdam , 2005.

[11] Hard-T, "Vehicles", Hyperloop Progress Paper (hardt.global)

[12] Daniel J. O'Connor et al. "Guide to Human Behavior in Fire." SFPE handbook of fire protection engineering, 2019.

[13] A. J. Higgins, "Vacuum Exposure, How long will it take a spacecraft to decompress?," https://web.archive.org/web/20090208103930/http://geoffreylandis.com/higgins.html.