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Boarding security of the Hyperloop system

Thesis Report

Hardt Hyperloop concept image. (HardtHyperloop, 2019)

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Summary

The Hyperloop concept is a new method of transportation. Considering this, it still has a vast amount of challenges to tackle and overcome. One of these challenges is the boarding security system, on which this research is focused.

The Hyperloop is a tube-based transport method. The pods in which passengers travel have to be entered via certain access points, since the tube is in near vacuum state and cannot be entered everywhere along its length. To ensure security and safety of the system's users, a boarding security system is required. In this report, the aim is to create the beginnings of a design of such a boarding security system.

Several already-existing transportation methods, which can be compared to the Hyperloop in one or a number of ways, were analyzed for their boarding security systems. Their boarding processes, risks and measures were noted. This was done by arranging each of the systems risks, related to boarding security, and combining these with their respective measures, costs and placement. The transportation methods which had the highest risks, also had the most and most extreme measures to combat these respective risks. The Hyperloop is a closed system. This enables it to be considered a high-risk system, mainly because emergency exits and access for help are hard to realize. Another aspect which increases risk, is the high velocity at which the Hyperloop is expected to operate. This high velocity can accelerate and multiply the resulting damage in case an accident happens. The most significant analyzed transportation method (in terms of amount of terrorist countermeasures) was the airplane. At an airport, a combination of cameras, active personnel (such as guards and camera surveillants) and extensive security checks are implemented to maximize security.
To custom fit a security system to the Hyperloop, the actual properties of the Hyperloop system itself have to be determined. Therefore, a certain variation of the Hyperloop was chosen out of several to further use in this report. The chosen variation has four key features; the tube is placed above ground surface level, the pods are sized to fit about 20 passengers, the transportation system can be used without reservation and the pods enter a pressurization room (locked and entered by gates) to make it possible for travelers to enter.
The risks of this specific system were determined to mostly be hijackings and bombings, this was done by analyzing terrorist attack statistics. Before determining the boarding security system's elements, limitations were set. These limitations limit (and change) the security measures, by implementing other factors that should be considered. This is an important part, since an overflow of security measures can increase overall system costs and therefore degrade user experience. These limitations were costs, time delays and differences in laws and culture per country. Costs were chosen to not be varied, since the overall security costs per ticket price are but a small portion of the expected overall ticket price (about €10 per flight per person for air travel, which will be used as a simplification). Two significant limitations are time delays and regional differences. Time delays reduce travel flow. Regional differences, like terror attack probability per nation, influence the required anti-measures. These two limitations are combined to create two versions of the boarding system. One version is automated, which costs less time but is possibly less safe. The other one is a partially automated system with manual additions, which takes up more workforce and time (e.g. by also performing checks by hand) but therefore increases security by broadening the overall security process. The implemented system will depend on the specific region.

The boarding security system consists out of the following components:

- An extensive camera surveillance system spread out over the entire station.

- Luggage and passenger check, which includes metal detectors, x-ray scanners and possibly explosive detection devices.

- A well-ordered, structured boarding procedure which enhances the capability to maintain an overall view on what is happening and what the passengers are doing. This means a mostly guided system, initiated once the traveler enters the station facility. The guiding of the travelers is to mainly happen via the station's layout; the positioning of gates and rails, which indicate the path passengers are to follow. This makes it easier for the personnel to spot extraordinary activities.

- A team of personnel to inspect the camera footage, perform checks in manual regions and operate as security guards and first-aid helpers.

As one can tell, the defined boarding security system above seems to resemble that of an airport. However, a key difference is that air flights are reserved. The Hyperloop, according to the assumed system used in this report, is not. Therefore, the 3rd point of the boarding security system (well-ordered boarding procedure) is of great importance. By increasing the structure in the system, it becomes easier for the personnel to focus on their respective function which can increase efficiency.

Preface

This report is a thesis project for the Bachelor of Civil Engineering, followed at the Delft University of Technology. The project was followed at the faculty of Civil Engineering, at the department of Transport & Planning.

I would like to give my greatest thanks to my supervisors, Dr. ir. A.M. Salomons and Ir. R.P. Koster, who guided me during this research. This was crucial in achieving the final result.

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1. Introduction

In the world of today, public security is a matter that is increasingly more important. This makes sense, considering the increase in technological progression. Not only technology itself becomes more complicated and varied, but also the way this technology can be sabotaged for the worse of the people. When considering a new method of transportation, these methods for causing harm increase even further. Therefore, it is important for any new method of transportation to have a well-thought-out security system to prevent malicious ideas from becoming reality. In this report, a theoretical security system is made for the boarding process of the Hyperloop.

1.1 The Hyperloop System

The Hyperloop system is a new proposed method of transportation of passengers and / or freight. The name ''Hyperloop'' was first used to describe a vactrain (vacuum tube train) concept design released by a collaborating team from SpaceX and Tesla. (Musk, 2013) The concept of a vactrain was first proposed by Robert Goddard in 1904, who mentioned a sealed tube in which a pod may travel free of air resistance. (Max, 2019)

Elon Musk's version of the concept uses a low-pressure tube in which pressurized pods can move freely. These pods flow on an air cushion that acts as the systems suspension. The pods are accelerated by linear induction motors. (Musk, 2013) In figure 1, an illustration of a concept Hyperloop design is shown.

The Hyperloop Alpha concept was published in 2013. In this paper, a route was proposed that ran from San Francisco to Los Angeles. The paper mentioned that a velocity of 1200 km/h could be achieved along this route, covering 560 km in just 35 minutes. This is faster than any current form of (publicly accessible) transportation. The expected costs were also calculated: 6 billion dollars for a passenger only version, 7.5 billion dollars for a version that could transport vehicles. (Musk, 2013)

The Hyperloop concept is now an open-source project. Several teams, from all over the world, have taken the idea and worked further upon it by themselves. TU Delft also has a team working on it, which is led by students, as more of the teams are. (DelftHyperloop, 2019)

Some scientists and engineers are skeptical about the new transportation concept. According to them, the technology is more expensive than first led to believe. Besides this, they think the Hyperloop is too vulnerable for disruption by accidents or terrorist attacks. (Wolverton, 2013)

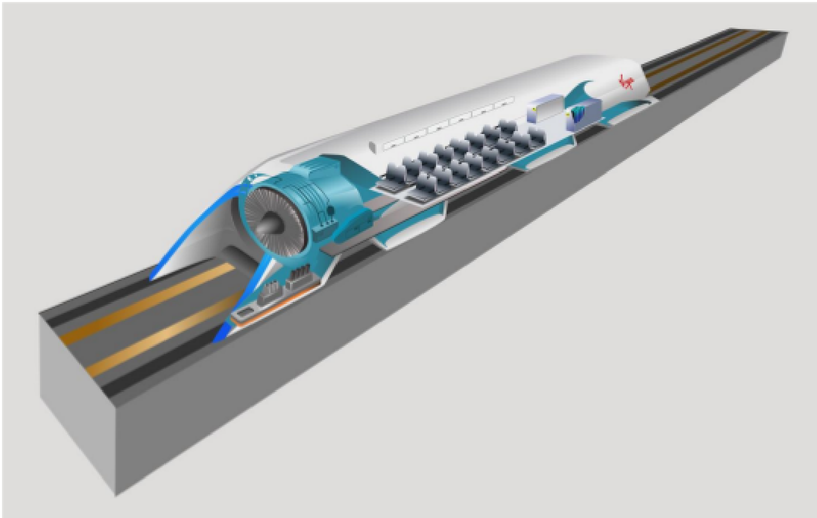

Figure 1. A concept sketch of the Virgin Aerospace Hyperloop. (Sanchez, 2015)

The goal is to design a system to secure the Hyperloop boarding process against terrorism in the most effective manner. Instead of directly focusing on the Hyperloop system, and thinking of ways to secure it against terrorism, it is a good idea to look at different transportation systems first. The Hyperloop is a very new system. It is so new in fact, it isn't even in use yet as of 2020. Other methods of transportation have been around for centuries or decennia, and thus have had to deal with lots of problem solving (including anti-terrorism, mainly since approximately 2000).

1.2 Public transport security

Public transport security refers to certain measures which are taken by a public transport system. These measures are to ensure the safety and protection of the systems users, employees and equipment. (Light) enforcement of several regulations is used to warrant these measures. In recent years, public transport security has become a more serious topic than ever before. In the USA, this was mostly because of the September 11 attacks. In Europe, the 2004 Madrid train bombings were the main cause of the increase in security. (Johnson, 2009)

Although it has been proposed that a security screening of passengers, and their luggage, is a good way to prevent attacks in public transport, some experts recommend against it. Their arguments being that the benefits do not outweigh the induced negative side effects for most public transport methods. Examples of said negative side effects are increased costs, vulnerable queues, reduced convenience and reduced civil liberties. (VillageVoice, 2005) In cases where the consequences of an attack would be drastically large, most governments do choose to implement a security system. A measure that is used more often nowadays, is prevention. Investigating and resolving malicious plans before they occur, seems to be one of the most effective anti-terror solutions. This measure, however, is not a part of boarding security and is therefore not analyzed further in this report. (Johnson, 2009)

1.3 Content of report chapters

In the 2nd chapter of this report, the methodology and design approach of the project is explained. Comparable transport systems are further investigated and analyzed in chapter 3. In the 4th chapter, the main elements concerning Hyperloop boarding security can be read. This includes the possible Hyperloop setups and their risks, as well as a first glance at the applicable security measures. This chapter also goes over the limitations of said security measures. In chapter 5 of the report, a final theoretical boarding security system is to be made. In the 6th chapter, the research project is discussed on its positive and negative quantities. Also, further research is recommended. In the final chapter, the conclusion of the research can be read.

2. Methodology & design approach

During this entire research, literature on the subjects in question is studied. Besides this, several experts on the fields of security and the Hyperloop have contributed to the requirement of needed information and knowledge. This literature and these expert contributions are key to investigate the current transportation methods and their anti-terror security measures. Literature study is performed by searching the internet and interviewing experts for terms and topics considering the Hyperloop system, as well as boarding security systems of alternative transportation methods. These terms and topics include: ''Hyperloop concept'', ''boarding security'' and ''public transport security''. The project is demarked by the boarding security part of the Hyperloop system.

2.1 Analysis of already-existing boarding security systems

Using the acquired knowledge from literature, the boarding process of similar transportation methods to the Hyperloop are be examined. The examination is done by studying what steps are involved in the boarding process, and the security hereof, for these systems. For these similar transportation systems, the following are used. As for the comparisons with the Hyperloop, the research is limited to these three transport systems. This is because, together, these three systems cover the most obvious properties of the Hyperloop system (speed, tunnel-based, enclosed vehicle without quick exit possibilities).

The Metro / Subway
Considering the Hyperloop could be used for daily commuting in the future, short distance travel could be an often-occurring way of use of the Hyperloop. Short distance travel, for this report, is defined as travel with a travel distance of about 15 kilometers (CBS, 2013). This is an interesting comparison, since the metro system is also often used for this kind of short distance travel. Another comparison is the large number of people boarding the system. It is interesting to analyze how the metro system deals with this challenge. (CBS, 2013).

The Channel Tunnel
The Hyperloop system is a tube-based system, as earlier mentioned. A system of this kind has the property to enclose the passenger and vehicle in a tunnel-like contraption. Considering the Channel Tunnel also has this property, it is interesting to see which measures are taken for the boarding security of this system.

Airplane
Air flight is a manner of public transport which has very high movement velocities. This corresponds with the Hyperloop is the sense that it also moves at a very high speed. When moving fast, small problems can escalate into big ones. This partially indicated the importance of a decent security system. Airports also deal with a large number of crowds, which makes security complex and needed even more. This could be a reason for terrorists to target this type of transport, since it can potentially result in disaster. Therefore, airplane boarding security is one of the strictest types of boarding security of all transport systems.

2.2 Hyperloop variations

When the boarding security systems of these transport systems have been inventoried, the next step in this research is to determine *which* Hyperloop system is going to be used for boarding security design. The Hyperloop is a new transportation method. There is not a definitive version of it, many of its aspects are still discussed. This is an important step, because the used variation determines the boarding process of the Hyperloop. For this research several options of the boarding system are discussed, which can be seen below.

- Reserved / non-reserved travel. This has impact on boarding security because it has an effect on station population density.
- Pod capacity. Larger pods could mean an increase in passenger discharge, which has an effect on security since it reduces the amount of people on the station. This element is further explained in section 4.1.
- Method of entering pod. Since the Hyperloop travels in a (almost) vacuum, entering and leaving a pod can be done in different ways. One of those ways is via a gate system which pressurizes a certain section of the tube, so boarding the pod is possible. To check whether this gate system is viable, the evacuation time of the pressurized system component is calculated.

The Hyperloop tube is near-vacuum, so its internal air pressure is not 0. The air pressure inside the tube equals to about 1/1000th atmosphere or 100 Pa. (InterestingEngineering, 2017) Using this information the evacuation time (time to achieve wanted pressure from starting pressure) can be calculated using equation 1. (EngineeringToolbox, 2019)

$$t = \frac{V}{q} \ln\left(\frac{p_0}{p_1}\right) \qquad (1)$$

Where:
t = evacuation time
V = volume of pressurization zone
q = pumping rate
p_0 = initial pressure
p_1 = end pressure

The evacuation time is calculated for 2 different pod capacities. These 2 capacities are mentioned in the *Pod Capacity* part of section 4.1. Capacity 1 is a pod for 20 people, capacity 2 is a pod for 100 people. The 20 people capacity is realistic in the sense that some developers consider this as a goal capacity. The 100 people capacity is unlikely to be realistic, but draws a good idea on evacuation time for larger pods (such as cargo pods). (USCHyperloop, 2019) The calculations follow in section 4.1.

2.3 Potential boarding process

Below, aspects that are part of a potential boarding process of the Hyperloop are assumed. This is further explained in chapter 4.

- Passengers enter the station.
- Passengers go through body screening and/or luggage check, or any other kind of checking such as facial recognition via security cameras.
- Passengers either go to pod-entering location, or wait in a general lobby. This depends on the reservation method of the system.
- Passengers enter the pod. How this happens, depend on the chosen method. One possible method is a gate-system, this means the pressure around the entire pod is atmospheric. In this case the passengers can get in line and enter the pod accordingly via a door. Another possible method is a docking system. In this case, the entrance to the pod is likely to be smaller, since the passengers have to go through the docking port. This could mean slower entry and exit times. This is further explained in section 4.1.

2.4 Mapping risks

An attempt is made to solve each of the mapped risks of the Hyperloop system. This is done by looking at a similar risk from other methods of transport and seeing what has been done to resolve it in that particular case, if it has been resolved at all. When a similar risk and solution are found, the solution is adjusted in such a way that it best fits the characteristics of the Hyperloop (high velocity, tunnel-based, possible high people concentration, operates on electricity). When differences in risks and measures occur, they're also further looked upon to extract new ideas from them.

When boarding the Hyperloop shuttle, the traveler commits to spending a significant amount of time in an enclosed capsule pod, together with unfamiliar fellow travelers. One of the risks is that one of these travelers wants to inflict physical damage to fellow passengers in the pod. It could also be possible for people to inflict damage before entering the pod, in the waiting area. This damage could be done to both people as materials. Damage can not only be inflicted directly by a malicious person, but also by devices or other systems. This could happen, for example, when an unchecked item ends up at a vulnerable part of the transport system. Since the Hyperloop is a system that relies heavily on computer systems, hackers could also impose a serious threat. Since the Hyperloop functions by using linear induction, a simple power outage could mean a complete lock-up of the system and thus its passengers.

The value of a risk needs to be calculated. This is done according to the following formula. (Talbot, 2018)

$$Risk = Chance * Consequence \qquad (2)$$

The chances are in units of frequency. The consequences are scores on a 1-10 scale, these scores are assumed. These assumptions are based on the amount of damage a certain event can cause. The more damage / inconvenience an event can cause, the higher it scores on the scale.

2.5 Limiting factors

Limitations have to be defined. This is an important step in the process of developing the Hyperloop boarding security system. The reason of this importance is that the design has to stay inside the boundaries of what is feasible. When one does not set up limitations, these boundaries are not defined. The limitations considered in this report are listed below.

- Costs. Costs are an important part of any transport method. When the boarding security of the Hyperloop becomes too expensive, ticket prices may increase which could result in fewer travelers.
- Travel flow. The Hyperloop system is famous for its promised travel speed. Introducing an elaborate boarding security system can delay overall travel flow. This could decrease the benefits of its velocity, especially on shorter distance journeys.
- International travel. Different countries have different laws and ideas of security and risks. These ideas are based on the present risks and resources available in these said countries and locations. This has to be considered, since the Hyperloop is a system suitable for international travel. To combat this problem, a right balance has to be found to create a compromise which enables the most amount of people to make use of the system while still being secure. A demarcation has to be made, since there are too many different countries and corresponding ideas to take them all into account. The demarcation can lead to a simplification of the solution.

The solutions are to be merged into one theoretical boarding security system. Its positive and negative effects are mapped out. An expected positive effect, compared to these other systems, is overall boarding security which results in passenger safety. An example of an expected negative effect is costs. Securing high speed travel to a significant extent can become expensive quickly. Another negative effect could be a decrease in travel flow.

3. Security systems and risks of comparable transport systems

The Hyperloop is a system of public transport, this means stations will also be required. From concepts, nothing is known about these stations except that they're the location where people will gather to enter and exit the transport system. (Musk, 2013) Without immediately stating any risks that could be present in this system, basic characteristics are prominent.

Security systems are systems which are meant to prevent and protect a person, building or organization from malicious threats, e.g. terrorist attacks (Cambridge). Security can be split up in two main sections: hardware and software. Both these elements work together in a security system to maximize efficiency and capability.

When setting up a security system for a new method of transport, it can help to look upon already existing security measures. In this chapter, several alternative (public) transportation methods are analyzed for their techniques and attributes to counter terrorism and therefore increase security.

3.1 Metro system

The subway system has been in use for hundreds of years. In all this time, hundreds of passengers were killed, and even more were injured, by bombings on metro systems. This way of transportation is extremely vulnerable to terrorist attacks. This weakness has been exploited by over 100 different terrorist organizations, from far-leftists to religious fanatics. Over 60 countries' metro systems have been targeted in the past half century. In the current millennium alone Madrid has fallen victim in 2004, Mumbai in 2008, Moscow in 2010, Brussels in 2016 and London in 2005 and 2017. (Borrion, 2017)

Certain factors and attributes of the metro system make it particularly vulnerable to these kinds of attacks. Most metro systems in less-developed countries (which are often inhabited by less-content people), as well as earlier versions of the system, have very weak security measures. This, in combination with a high concentration of people, makes them prime targets for terrorists who want to afflict maximum damage. However, there are several measures that are taken by some countries' authorities to make this system more secure.

Installing complicated security checks at these metro stations would probably decrease the number of tragedies to happen. However, a lot of people would combat this security measure. Implementing these security checks would add a lot of time to a passenger's travel time, especially during rush hours.

Subways are open architecture systems. This means they're designed to have the minimum number of bottlenecks to keep the flow of people going. Less people mean more transparency, hence less danger. This is a double-edged sword however, since this technique also makes it easier for potential terrorists to enter. (Tene, 2017)

The London subway system is surveyed by a vast network of cameras, their purpose to identify suspicious behavior. This is their only on-site security measure; the rest is done by national intelligence to disrupt the plots at the planning stage.

On the other end of the spectrum, lay the Chinese, Indian and Russian metro systems. In these countries, every passenger (including luggage) is scanned for explosives and weapons. As earlier mentioned, this increases travel time significantly. In most cases, this can be up to a 20 minutes increase in travel time. However, since terrorism is a greater threat in those countries, increasing passenger travel time is a small price to pay. (Hainen, 2013)

The boarding process of the metro system is quite straightforward;

- Travelers enter the station, this is usually done by descending a few meters since the metro is of course underground.
This imposes the first threat. By entering the metro, people confine themselves in an underground, partially enclosed area. This leads to the first occurrence of crowd formation. To keep an eye on the situation, metro systems worldwide use of security cameras.

- The passengers head towards the designated gates / platforms.
This step of the boarding procedure causes standstill of passenger flow. As mentioned above, some countries do have extended measures for this step. They combat the issue by having security checks on people and luggage. Besides this, they also have personnel standing around for extra safety. Other countries choose to take no extra measures in this step of the boarding process, besides the camera surveillance.

- The passengers enter the metro vehicle.
In the stricter countries and places, mentioned above, this process is guarded by active personnel as well as camera surveillance. In most places, this part of boarding is also just surveyed by cameras.

3.2 Channel tunnel

Another tunnel-based public transport method is the Eurotunnel shuttle. Like the Hyperloop, the Eurotunnel is a long distance and high-speed transport method. Although the speeds don't go as high as the Hyperloop's, it could bring some good ideas to the table.

''With the current level of threat to national security, operators of the Ports and Channel Tunnel face increased requirements to ensure the security of their property, the ships, and trains that transit the Channel Tunnel.'' (Eurotunnel, coach operators, 2019). Because of this, the coaches and passengers may be subjected to a variation of different security measures. If the staff is not content with the security aspect of a passenger, they could even refuse travel. For example, when the passenger acts suspicious and won't agree with a further luggage search or investigation.

The Eurotunnel travel system is only accessible to those who have a legitimate reason to travel. Having a ''legitimate reason'' means an individual has to be able to indicate why they want to visit the country of destination. The crew ensures that no person can board the coaches without a valid form of authorization. The coach crew also makes sure of it that the number of passengers on board matches their records for that specific journey. This way, it isn't possible for ''lost'' luggage without a matching person to stay on the coach. This check is performed at the beginning (right before boarding) and end of every journey, to make sure no lost luggage remains in the system.

All baggage undergoes thorough checking before being allowed unto the coach. X-ray scanning devices are used to examine the luggage for illicit materials. When the luggage is checked and determined to be secure, it is allowed for the passenger to keep it with them during travel. To make sure no one bypasses this system, the coach crew personnel are the only people allowed to execute this procedure. This way, all luggage also ends up in the same computer system which makes it easy to monitor. (Eurotunnel, www.eurotunnel.com, 2019)

The boarding process of the Channel Tunnel is a bit more complex than the metro system (Eurotunnel, Traveling with us, 2019);

- The Channel tunnel journey begins with the arriving terminal. Here, the first clustering of people occurs.
To enter this area, you need to show your booking number as well as the used card number for the booking. From this point on, constant camera surveillance is present. This area has active personnel to keep an eye on the situation.

- Next follows the check-in procedure and border control.
This involves waiting, which causes a big clustering of travelers. Border control checks the persons reason for travel. Besides this, the camera and personnel surveillance combination actively guarantee security as best as possible.

- When this is done, the luggage, person and possibly vehicle are checked.
When in the tunnel, being secure is a tough prospect. Therefore, the Channel Tunnel security system first checks the people and their belongings for hazardous items. This includes luggage check and computer tracking hereof. In case of not complying to the security demands of the personnel, the traveler can be refused from the Channel Tunnel.

3.3 Airports

A large number of people in a confined space, means possible danger. Airports are among the busiest places in the world. At some airports, millions of people pass through each day. This makes airports attractive potential targets for terrorist attacks. Besides the airports, the airplanes themselves are also a prime example of this; a large number of people in an extremely confined space (without any immediate escape possibilities). Partially because of this, terrorist attacks on these items often end in high death rates. It is therefore extremely important to secure them in such a way, that the possibility for disaster is minimized. (Schneier, 2004)

An airport's security system uses a number of different parties to ensure its goal. This, of course, changes per nation. An extended report is given of airport security, since we want to learn from it to find usable methods to apply to the Hyperloop system.

Some examples of these parties are:
A police force can be hired and dedicated to the airport. This is for example done in Ireland, called

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the *Irish Airport Police Service*.
Police dog services, which are used for detection of illicit materials such as explosives or drugs. (AFP.gov.au, 2008)

3
Some incidents, e.g. airplane hijacking, can be the result of travelers carrying weapons (or items that could be used as weapons) on board. To counter this, airports are using state-of-the-art technologies. Nearly every commercial airport has metal detectors, which can detect metal objects which could potentially be weapons (knives, guns, etc.). Countries like the united states even use Explosive detection machines nowadays, which can detect certain chemicals which are linked to being used in explosive devices. These often go paired with an x-ray device to see inside of the luggage without opening it. Using these x-ray machines, time is saved during the check procedure since not every bag and suitcase has to be manually opened. When a suspicious shape or object is seen via the x-ray machine, the luggage is set aside for further examination. An image displaying a combination of an x-ray device and metal detector is shown below (figure 2). The restrictions on what is allowed depends on the type of cargo it is in. Airplanes have a luggage compartment, which is inaccessible during flight. The rules on what is allowed in these compartments is usually less strict than the rules that apply on hand-carry luggage. This allows people to still bring their ''potential weapons'' with them to their desired location.

The used machinery is, overall, pretty reliable, its failure rate is close to 0. (Rapiscan, 2019) In some countries, however, the airport finds it necessary to complete its checking process by specially trained personnel. This personnel selects travelers which stand out, or seem suspicious for any reason. Oftentimes this confrontation will be as much a quick conversation. Sometimes, however, it could go as far as a full body search.

These techniques, however, can also cause discomfort for the passenger. The (metal)detecting machines require users to take of any metal objects. Some older detectors even require the user to take of his or her shoes. This isn't just a hassle, but also takes some time since it's needed to wait in line. When an individual is personally examined, his / her waiting time will increase even more.

Restrictions to accessibility are also often (almost always) implied. Certain areas of the airport are inaccessible for people who haven't gone through the thorough checking procedure. Some areas aren't accessible to any travelers, for safety and security concerns.

A technique which is also often used in airport transportation, is camera surveillance. This is a method which is used in a lot of public transport systems. The security benefit it brings is that it makes it easier to keep an eye on the overall situation. Since there can be so many people at an airport, it's very difficult to oversee the entire situation just using personnel. The benefit of this security measure is that it's a relatively easily applicable system. Besides that, it doesn't cause much discomfort for the traveler. (Strauss, 2012)

The boarding process of an airplane is perhaps currently the most secure boarding process;

- Travelers enter the airport, which causes increase in population concentration.
From this point, and even slightly before it, camera systems record almost all actions. In most cases, personnel are also present in the entrance lobby.

- The passengers check in their luggage.
Waiting lines are created. This luggage check-in process is a measure in its own. Although the created waiting lines bring another hazard with them (gathering of people susceptible to an attack), the

measure is there in the first place to prevent the main luggage from being accessible during flight. To counter this, the perimeter is controlled by personnel (such as guards) and cameras.

- Passengers go through security check.
During this check, the passenger as well as their hand-luggage are checked thoroughly. As mentioned earlier, this is done by using a combination of metal detectors, x-ray scanners and possibly explosive detecting devices. In some cases, even dogs are used to detect potentially dangerous chemicals. During this process, the crowd is observed again by cameras and airport personnel. Passports are checked, to make sure nobody wanted by the police or government is able to travel abroad.

- The final part is the physical boarding of the airplane.
During this part, any potential hazardous items *should* be caught by the system. In case the system failed, guards and cameras are present to detect threats as fast as possible.

Figure 2. Combination of x-ray scanner and metal detector, for luggage and travelers respectively. (Davies, 2012)

3.4 Overview

It can be said that all three transportation methods have significant differences in their boarding security systems. Although all mentioned transportation methods are similar to the Hyperloop in one or several ways, the differences seem too notable to neglect. The main difference between each of the above systems is security severity. In table 1 the boarding security measures taken by the different transport methods are shown. Herein, the costs of measures are also displayed. Important is that the more advanced a system's security measures are, the higher the overall costs are. A large portion of these costs include yearly recurring costs. Since technology advances at a rapid rate, equipment has to be updated very regularly to maintain top quality. Since the security costs are so significant, it makes it clearer why several transportation methods choose to limit their measures.

The noted measures can further be combined to form a new boarding security system, which is applicable to the Hyperloop system.

Table 1. Comparison of different security elements and their usage. (Gillen, 2015) (Hainen, 2013) (Odgen, 2018) (Sawant, 2017)

	Metro	Channel Tunnel	Airport	Cost (Time)	Cost (Money)	Where
Cameras	Yes	Yes	Yes	Executed by active personnel, no extra time cost	Up to €400 per camera	Everywhere
Passenger and luggage scan	Depends on country, mostly no	Yes	Yes	Up to 60 minutes or more	Up to €200.000 per combination unit	When entering zone exclusive to passengers
Active personnel; guards, camera observers, (luggage) checkers	Depends on country, mostly no	Yes	Yes	/	Up to €20 per hour per person	Throughout the station
Computer system tracking	No	Yes	Yes	/	Up to €2.000.000 per year for automated systems	Initiated after luggage check
Required reason to travel	No	Yes	No	/	/	/
Inaccessible luggage / luggage system	No	No	Yes	Up to 30 minutes or more	Up to €7.000.000 per year for automated systems	When entering zone exclusive to passengers
Explosive sniffing dogs	No	No	Depends on country	Executed while travelers are waiting, no extra time cost	€1.250.000 per year	When entering zone exclusive to passengers

4. Hyperloop security

4.1 Alternative Hyperloop systems

Considering the Hyperloop system is still a concept system, some important properties hereof (listed below) aren't fully established yet. To generate a decent boarding security system for this new method of transportation, it is key to have an idea of what the complete system looks like and how it will function. Because of the uncertainties, several different versions of the Hyperloop are assumed. The system properties discussed in this report are the following.

4.1.1 Sub- or super surface Hyperloop tube

The manner of travel, below or above the ground in this case, is an important factor of overall security. Terrorist attacks could be different per situation. When the system is sub surface, the only way to reach it would be via the boarding stations. When the system lays above ground, attacks could be done by attacking the tube itself. This could mean that in the situation of a subsurface Hyperloop, the boarding security should be somewhat more extreme since more terrorist traffic could try to reach the system via here. If catastrophe would strike, the consequences have the tendency to be more disastrous if underground. Here, it would be significantly harder for help to reach the possible victims and Hyperloop system. Therefore, this could be another reason for terrorists to favor this type of system which they can reach via the boarding stations.

4.1.2 Method of vehicle entry

The tube through which the Hyperloop pods go contains a very low air pressure, near vacuum (1/1000th atmosphere) (InterestingEngineering, 2017). Of course, there has to be a way for people (or freight) to enter and leave these pods. This has to be done without breaking the vacuum seal and releasing air into the tube, since it would cost a lot of energy and time to lower the air pressure in the tube again. Two main methods of entry and exit are considered. The first one is a gate system. When the pods enter the station, they pass through a gate. When the pod comes to a standstill, the gate is closed. Now the area which the pod is in is pressurized to atmospheric pressure. Since a relatively large volume (quantification below) has to be pressurized, and depressurized once the pod leaves again, this process could take up a lot of time. A brief calculation of the required time is shown in table 2.

For a pod with a capacity of about 20 passengers, the estimated length is 10 meters with a diameter of 3 meters. A pod that would contain 100 passengers would have a length of 50 meters with a diameter of 3 meters. A possible tube diameter, accompanying the said pod diameter, is 4 meters. This would result in 0.5m of play around the pod. (SpaceX, 2017) From this we can obtain the net volume. A usual assumable pumping discharge for this application is 1 m^3/s. (EngineeringToolbox, 2019) In table 2, the evacuation time for both scenarios is shown using equation 1.

Table 2. Evacuation time per pod capacity. Results are rounded to nearest integer.

Capacity	Net volume ($V_{tube} - V_{pod}$) (m^3)	Pumping rate (m^3/s)	Initial pressure (mBar)	End pressure (mBar)	Evacuation time (s)
20 people	55	1	1000	1	380
100 people	275	1	1000	1	1900

The second possible option would be for the pods themselves to never leave the low-pressure zone. This would mean that the pods have some sort of docking port with the station, through which passengers and cargo can enter and exit the pods. There isn't any real-world application yet that uses this docking system, except for spacecraft. This procedure can take up to approximately 2 hours. (NASA, 2019)

4.1.3 Reservations

Reservations are a method to possibly decrease the number of waiting people. It means that people can arrive when they know they board a pod at a specific time. Using this method, the boarding security of the Hyperloop can increase. Since the use of reservations could mean a smaller amount of people waiting, the overall security is easier to oversee.
A variation on this would be to use time-slots for boarding. This means a person doesn't reserve a particular seat of a particular pod, but can access the system and use any pod within a certain time frame. Spreading out users over a relatively large time period could decrease congestion within a station, at e.g. rush hour.
These reservations, however, can prohibit the Hyperloop from becoming a widely used system. It is expected people are not likely to use the Hyperloop as commuting transport if they are asked to reserve their travel daily.

Deciding not to use reservations for the system can have its benefits as well. A non-reserved system can be used whenever the traveler wants to use it (assuming a pod-seat is available). A system of this kind could fit better in the fast-paced world of today. It could also lead to a smoother, and faster, transition of the Hyperloop to a widely used transportation system.

4.1.4 Pod capacity

Pod capacity and reservations influence each other. When travelers reserve their seat up front, it is possible to use larger and fewer pods. This is because a larger set of travelers could be assigned to a certain pod at a certain time. When no journeys are planned, the station will be nearly empty. This does bring one significant threat along though. When a large pod is planned to leave, a large number of passengers will enter the station in a relatively small amount of time. This requires good people management and temporarily puts strain on the boarding security system.

It is also possible to combine reservations with small Hyperloop pods. This could be done by creating time slots for which passengers can reserve the right to a seat, as mentioned above. This, however, would not be a viable option for commuting transport. People want to be able to go to work, and home, when necessary. Users of the system cannot be expected to arrive significantly too soon at work, or leave later than wanted, because they do not have a reservation for e.g. the rush hour time slot. Because of this reason, this possibility is not further examined in this report.

From this, two viable options remain: large pod capacity with reservation, or small pod capacity without reservations. Large pod capacity, in this case, means circa 100 people. Small pod capacity means circa 20 people. These numbers are based on the goal of transporting circa 800 people per hour (USCHyperloop, 2019). Large reserved pods are to leave the station 8 times every hour (once every 7.5 minutes). Small non-reserved pods are to leave the station 40 times every hour (once every 1.5 minutes).

This means that multiple departure locations (tubes) are mandatory, since these said frequencies cannot be achieved with a single departure point. This is because the pressurization times, which are stated in table 2, exceed the maximum time gaps required to fulfill the wanted frequencies. However, this does not necessarily pose a problem since a Hyperloop station with such a traveler flow is expected to have multiple tubes anyway (in different directions).

4.1.5 Possible variations

As a result, there are 8 possibilities for the Hyperloop system. They can be seen in table 3 below. In section 4.3, one of these variations is to be chosen as the representative Hyperloop version considered in this report.

Table 3. Possible configurations of the Hyperloop varieties.

	Sub- or super surface tube	Method of vehicle entry	Reservations / pod capacity
Variation 1	Sub surface	Gate	Large Reserved
Variation 2	Sub surface	Gate	Small non-reserved
Variation 3	Sub surface	Docking	Large Reserved
Variation 4	Sub surface	Docking	Small non-reserved
Variation 5	Super surface	Gate	Large Reserved
Variation 6	Super surface	Gate	Small non-reserved
Variation 7	Super surface	Docking	Large Reserved
Variation 8	Super surface	Docking	Small non-reserved

4.2 Risks

The boarding process of the Hyperloop is a vulnerable part of the system. During this process, passengers and equipment are susceptive to different types of risks. Listing the boarding process steps is necessary to later create a boarding security system.

Below, the boarding process is described step by step. With each step, the imposed possible calamity is mentioned. Further in this chapter, these risks are quantized by using equation 2.

The boarding process:

- The travelers enter the Hyperloop station. At this point the group formation starts. This could be the first dangerous part of the system. A cluster of people means a potential target.

- The passengers make their way to the correct boarding location, or wait around and possibly have a drink or something to eat. This depends on the implemented system. When the system is non-reservation-based, the passengers are more likely to go directly to the boarding location instead of lingering around. Another clustering of people occurs in this step.

- Luggage and passenger check (optional measure). This is an event that passengers come across on their way to the boarding gate. Again, it causes clustering of people.

- The final step is entering the vehicle. At this location, the main tube can be accessed. Therefore, inflicting damage here can lead to greater results than other location on the station. A bomb could be detonated at the gate / docking port, breaking the vacuum seal and causing heavy expenses. Another possibility here is the chance of a hijacking. Since large crowds form here again, the chance of targeting people in an attack also occurs.

The chances of these occurrences change per event. Below, in table 3, the possible calamities are presented including their probability of occurrence. These values are determined by investigating the frequency of airplane / airport incidents. Therefore, they aren't exactly applicable to the Hyperloop but give a good initial idea of terrorist actions.

Table 3. Likelihood of occurrence per event if an event occurs at all. Overall probability of event occurrence is roughly 1 in 16 million. (Silver, 2009) (RandDatabase, 2009)

Event	*Likelihood of occurrence (%)*
Hijack	43
Bomb	24
Cargo bomb	5
Hijack-crash	24
Other	4

In table 4, the consequences of these calamities are shown for each occurrence.

Table 4. The consequences per possible event. (Gelder, 2019)

Event	*Consequence*
Hijack	Time delay Possibility human injury
Bomb	Extreme time delay Damaged equipment Very high possibility of human injury
Cargo bomb	Extreme time delay Damaged equipment High possibility of human injury
Hijack-crash	Extreme time delay Damaged equipment Very high possibility of human injury
Other	/

These events are given scores on how large their impact (consequence) is to the system and society. The events are rated on a scale from 1 to 10. These ratings are based on a simplificated quantification of the values of table 4, e.g. ''very high possibility of human injury'' scores high while ''time delay'' scores low on the scale. These scores may vary depending on who assigns them. The rated scores are multiplied with the probability of the corresponding event to obtain risk, according to equation 2. In table 5, the types of events are displayed together with their likelihood in case an event occurs, consequence score and risk. The consequence score for *other* is set as the median of the scale; 5.5, since this could involve any occurrence and the ''Law of Large Numbers'' states the average will be the median of the scale. (Grimmett, 1992)

Table 5. Events, probability, consequence score and their corresponding risks.

Event	*Probability (%)*	*Consequence score*	*Risk*
Hijack	43	6.5	2.8
Hijack-Crash	24	10	2.4
Bomb	24	10	2.4
Cargo bomb	5	8	0.4
Other	4	5.5	0.2

4.3 Possible security elements to be implemented

The possible threats that deserve the most attention are hijacks and passenger bombings. Cargo bombings and other possibilities should still be considered, but not as in-depth.

4.3.1 The variation to be used

Hijacks/ hijacks-crashes and bombings are the most prominent risks of the Hyperloop system. Although airplane hijacks are different from Hyperloop hijacks, the basic idea is the over-taking of a pod and halting / changing its intended direction. The terrorist's possibilities with the Hyperloop are limited compared to airplanes, but the possible inflicted terror isn't necessarily less. Therefore, the boarding security system should be designed in such a way that the overall probabilities are minimized. The first thing to consider is pod capacity. Higher capacities mean a larger number of potential hostages and / or victims. It would therefore be beneficial to security if the pods are of the smaller variety. In case of a hijacking or bombing, it is important for helping personnel to reach the situation as best as possible. This would tend to a variation that includes a super surface Hyperloop. Since the smaller Hyperloop pods are used, the gate boarding system becomes more logical. The evacuation time (to reach atmospheric pressure) of the smaller pods was around 6 minutes. This short process increases security since it increases flow of travelers. The resulting Hyperloop variation which is further used will therefore be **variation 6** (see table 3 or relevant part of table 3 below).

Variation 6	Super surface	Gate	Small non-reserved

4.3.2 Measures

Based on the risks of the Hyperloop system, the boarding security measures can be determined.

- When the travelers board the station, an extensive camera system can be very beneficial. (Li, 2019) This system can lessen threats in 2 ways. Firstly, the presence of a camera system gives people the feeling that they are being watched, which can reduce initial plans to execute malicious thoughts. Secondly, an active staff of personnel can observe the crowd to scan for suspicious people.

- When travelers head towards the boarding gate, it is important to have an extended check. Hijacks, and of course bombings too, are executed with certain items. When a person is separated from these items before their plan initiates, the plan is likely to be disbanded. This said check should include metal detectors, x-ray scanners and even possibly explosive detection devices. Applying this measure also aids in prevention of ideas in general, as explained above with the camera system measure.

- At the physical boarding phase of the system, a structured boarding order is desired. Since the system is reservation-less, this has to be achieved in a different way than e.g. airport boarding systems. The idea is to have structured lines before the multiple entrance gates of the pods, guiding the travelers via an easily monitorable line comparable to theme park waiting lines. Travelers are requested to wait in line until it is their time to board the capsule. This process is constantly monitored by cameras as well as active personnel, to ensure people follow procedure.

4.4 Limit of security

There are several elements which should be considered when the Hyperloop boarding security is determined. These elements could potentially limit the security measures taken. Below, several of these elements are mentioned and explained.

4.4.1 Costs

Increasing the level of security (almost) always means increasing machinery or personnel. These extra costs are, eventually, paid by the user. In figure 3, people's opinions of acceptable ticket prices are shown. The results are taken from a survey, in which a minimum of 100 randomly selected participants were asked their opinion. (Krom, 2019) In this figure, it can be seen that most people aren't willing to pay as much for a Hyperloop ticket as they would for an airplane ticket. This could be explained by stating that the Hyperloop is a new method of transportation. Therefore, it has not convinced people yet of its capabilities. Some are however prepared to pay extra for the Hyperloop, which could be explained by curiosity towards a new technology.

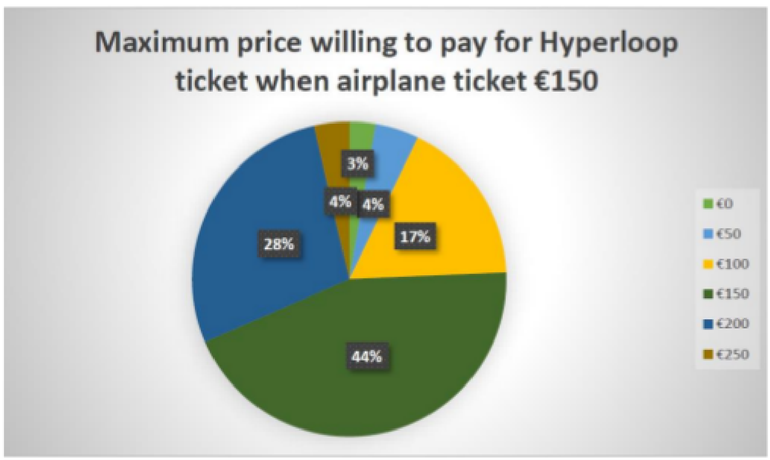

Figure 3. People's willingness to pay for a Hyperloop ticket if price is x amount compared to a €150 airplane ticket. (Krom, 2019)

To encourage Hyperloop usage anyway, the ticket costs should be minimized. The security measures are however somewhat the same as most airports have. This level of security costs a certain amount of money. At airports, it adds to about €10 extra per ticket. (Jeffrey Price, 2016) These €10 are relatively insignificant compared to the displayed prices (in figure 3) with an average of €150. Since these €10 change so little to the ticket price, it's recommended to stick to the boarding security measures in section 4.3.

4.4.2 Travel flow

Travel flow is another important limitation. Travelers want to reach their destination as fast as possible. To minimize the decrease in travel flow, while still retaining the measures needed, the following technique is advised;

To maintain flow in the boarding process, it is advisable to integrate the entire boarding process as an automated system. Travelers would go through the security checks on their own, just like people go through the check-in gates at modern day Dutch train stations. Artificial Intelligence (in combination with facial recognition) can be used to scan and check passports quickly, so it can be done at each journey. Active personnel are around to keep an eye on everyone, but do not interfere unless necessary. Boarding the pods is done in a similar fashion as rollercoasters in theme parks, by forcing people to form lines. This will force travelers to wait on their turn to board, therefore decreasing congestion which often occurs at other transport methods (such as trains). Automating this boarding system can reduce overall required times. This automation seems easier to apply to a Hyperloop station than, for example, an airport for a number of reasons. First, Hyperloop pods are smaller which results in a smaller number of people grouping together through the automatization process. Second, the Hyperloop is expected to be a relatively precise system (relatively) free of environmental effects. If the pods arrive and depart on strictly set times, an automatization process becomes easier to implement.

4.4.3 International travel

Consider two options, low-risk and high-risk locations of Hyperloop stations. To determine whether a location is high- or low-risk, the frequency of terrorist attacks should be considered. This grading system can be based on the Dutch threat level system. This Dutch system grades the current situation on a scale from 1 to 5, where 5 is the highest threat level. (NCTV, 2019)
For the low-risk option, the boarding process is as automated as much as possible. Active personnel is present, but with limited amounts and limited strictness (personnel can have more variating functions and tasks since a large part is done by automatization).
For the high-risk option, this is done differently. The amount of active personnel will increase. They will actively do checks manually instead of automated. The overall system measures stay the same, but manual instead of automatic. This doesn't necessarily make it more secure, but intimidates possible perpetrators from carrying out their plans. Armed guards stand guard in this situation, whereas in the low-risk option this isn't the case.

5. Results

When analyzing alternative transportation methods, several measures were found. These can be seen in *table 1* at the end of chapter 3. As one can see, the measures taken depend heavily on the transportation method in question. Besides that, different regions and countries have different measures to tackle threats.

At first sight, the fact that boarding security systems differ per transportation method doesn't necessarily make sense. One would believe security, as well as safety in general, is a top-class priority. However, the discovered data (as seen in table 1) suggests that this is not the case in all situations. Factors as costs, travel flow and regional limitations are the cause of compromises which limit the level of (boarding) security. The findings per limitation are displayed in table 6 below. These findings were derived from analyzed literature on the subjects.

Table 6. Limitations of a boarding security system and their respective findings.

Limitation	**Findings**
Costs	Increased ticket price because boarding security costs is estimated at €10 per ticket
Travel flow	Travel time is considered an important element of transportation. A certain change to the system which increases travel flow could help
International travel	Different regions in the world have different threat probabilities

For people to gain trust in the Hyperloop system, it is especially important for the system to have as few as possible malfunctions (including human-induced errors) in its early years. Therefore, a relatively small increase in ticket price is considered a good compromise for increased safety. This design ideology corresponds somewhat with the boarding security systems of airports. Figure 3 indicates most people would not base their ticket purchase decision on a deviation of such magnitude anyway. Hyperloop ticket pricing is estimated at about the same pricing of air flights for the same distance, based on what users are willing to pay. (Krom, 2019) This would mean e.g. €60 for a flight from Amsterdam to Berlin, which translates to about €10 per 100 km. (GoogleFlights, retrieved 2020)

The risks, derived from the probabilities of attacks and a linked consequence score, are noted in *table 5* in section 4.2. The main threats to a transportation device as the Hyperloop turn out to be hijackings and bombings. This information was acquired by investigating terrorist attack rates on aircraft and airports. This means the data is not exactly representative and could be different for the Hyperloop, however it does give a decent impression of the probabilities of an attack and the state-of-mind of the extremist.

From this results an assumption that the Hyperloop boarding security system could have one or more overlaps with an airport boarding security system. However, the Hyperloop version used for this particular research does not have a reservation-based boarding system.

Different regions can have massively different levels of threat and ideas of security. Therefore, each station of a Hyperloop line (station to station) can have one of two possible boarding security systems. The details of each system are explained below. The chosen system depends on the level of threat corresponding to that particular region. For the Netherlands this level is taken from the National Threat Level determined by the government. A minimum score of 4 on the scale from 1 to 5 is required for Boarding security option 2 to be initiated. The system is set-up in such a way, that every station can switch between option 1 (low risk) and option 2 (high risk) depending on the current threat level.

The Hyperloops theoretical boarding systems are described below. The travelers' journey is broken down into 3 phases. For each phase, the systems characteristics are mentioned.

5.1 Option 1: Low threat level

Phase 1: Entering a designated Hyperloop station.

An extensive camera set-up monitors travelers from the point they enter the station. This can increase security in two main ways; firstly, the camera surveillance staff can observe the travelers' behavior in an efficient manner. This element of the system is not automated, since humans are better at interpreting suspicious human behavior than machines. Secondly, the presence of cameras gives people the feeling of being watched. This could help prevent malicious acts. (Li, 2019) This camera system is present in the entirety of the boarding process.

Phase 2: Path to boarding gate

Here, a security check is done for each passenger and their luggage. This consists of metal detectors and x-ray scanners. This checking process is mostly automated. The passport checks are performed by the help of AI (artificial intelligence), which uses facial recognition software to verify passports correspond to the passenger. This software can also be linked to a databank, which recognizes wanted travelers. The luggage checks are to be automated by using a conveyor belt. Passengers can place their luggage hereon, after which it will pass through the scanners and be collected later on. For observation of the luggage, it is advised a combination of shape recognition AI and personnel is used. The travelers are checked by metal detectors, through which these travelers walk one after another.

Phase 3: Physical boarding of Hyperloop pod

To maintain structure in the boarding of the pod, lines are formed for each entry point of the pod. The way this functions is comparable to waiting lines for theme park rides. In this case, however, a lighting system can be used to indicate which lines are shortest (and longest). This way, people can always join the shortest waiting lines which reduces overall waiting times. The mentioned lighting system works in a similar way as traffic lights, showing green when the line is short and red when it is long.

5.2 Option 2: High threat level

Phase 1: Entering a designated Hyperloop station.

Here, the camera component from the low threat level is also present. Besides this, the entrance and entrance hall of the station is accompanied with guards. The presence of guards further enhances the preventive properties of the camera system.

Phase 2: Path to boarding gate

The passenger- and luggage checks are more extensive. An explosive detection device is added to the standard luggage scan process. More staff is present. This extra staff can routinely search luggage manually. In case necessary, armed guards are present to intervene a potential calamity.

Phase 3: Physical boarding of Hyperloop pod

Passengers are assigned a waiting line to join, just as is option 1. In this option, however, personnel make sure the passengers follow strict boarding procedure to make sure the situation is under control. Guards are present to intervene in case one or more people try to cause harm.

As for the costs and time delay properties of both options, there is not much quantitively to say. This is because these factors depend heavily on the specific station, day and time of day. However, when comparing these two options with each other, the factors that add costs and time delays can be noted. Since option 2 involves more security guards and manual labor, the main increase in costs (compared to option 1) would come from the extra personnel. The extra work that said personnel manually performs is a factor which adds time delay to the boarding process.

6. Discussion

At the basis of this research lays the analysis of alternative transport systems boarding security. These were used to get an understanding of the present-day methods used to ensure this transport boarding security. For this report, three comparable transport systems were analyzed. Their characteristics were noted. In hindsight, it could have been better to use a larger pool of transportation methods as basis such as ferry's and high-speed trains (Thalys, Bullet train). The larger the research pool, the more security measures could come out as a result. An increased catalog of possible measures could mean a more fit-for-purpose security system as a result. This is a matter which could be further expanded in possible future research.

In this research, several assumptions have been made concerning the Hyperloop system design. These assumptions had to be made, to create a quasi-definitive version of the Hyperloop on which the boarding system could be based. One could say these assumptions were chosen in favor of boarding security. In the future, when the Hyperloop system's development is further advanced than it is today, it is possible that the actual Hyperloop varies from this report's version. For future research regarding this report's topic, it is advised to re-analyze the current development status of the Hyperloop.

The Hyperloop version determined for use in this report is placed super-surface. This ensures easy access in case anything goes wrong inside of the tube. This also decreases the risk of an attack at the boarding stage of the system. This is because the rest of the system becomes more vulnerable (easily accessible since it is above the ground), which may cause terrorists to direct their attacks on the tube itself. This, as one could imagine, is not a wanted feature of the system. However, measures to minimize this threat fall out of this projects scope. For the system, a non-reserved travel base is chosen. In favor of this, it is beneficial to have a higher frequency of pod arrival and departure in combination with smaller capacity pods (~20 passengers per pod). This frequency does require the availability of multiple tubes per station, since the time between departures is shorter than the pressurization time needed for boarding. This seems reasonable, since most high-usage public transportation services have multiple vehicles which travel in different directions.

As for the risks concerning the Hyperloop project, statistics of aircraft and airports have been used to determine probabilities. This was done, since this report's research indicated several major comparisons between the two systems. As mentioned above, using a greater variety of comparable transport methods could lead to a different result. The findings from said statistics were interesting. Hijacks were the most often occurring terrorist activity. This phenomenon is different when applied to the Hyperloop. An airplane can be instructed to go wherever, while a Hyperloop pod is restricted to two directions. One could argue that this would reduce the probability of such an event from happening. However, this can not be stated without further investigation.

Also important are the chosen consequence scores, used to determine the risks. These consequence scores were partially based on the amount of damage the corresponding event could cause. However, since the Hyperloop is still in its concept stage, these damages (expressed in costs) are likely to change in the future. Said consequence scores are also partially subjective. When a different person has to assign these, chances are that the results differ.

Different regions can have massively different levels of threat and ideas of security. Therefore, each station of a Hyperloop line (station to station) can have one of two possible boarding security systems. The details of each system are explained below. The chosen system depends on the level of threat corresponding to that particular region. For the Netherlands this level is taken from the National Threat Level determined by the government. This threat level is determined by a group of experts in the field of anti-terrorism. However, it does remain a somewhat subjective form of reasoning.

To determine the final (theoretical) boarding security system, several limitations were defined. In this report, those were costs, travel flow and regional differences. For future research, it is advised to broaden this catalog. More limitations could result in a different system than is concluded in this report. From analyzing these limitations, it was found that regional differences have the highest impact on boarding security. This factor somewhat influences costs and travel flow, because the significance of those two factors is partially determined by the location of interest. Costs were found to be relatively insignificant for a system with high ticket pricing, like the Hyperloop is expected to have.

The overall defined boarding security system of the Hyperloop has several uncertainties and assumptions in its core. This seems normal, because of the early stage that the transport system is in.

7. Conclusion

To get an understanding of which boarding security measures are available, three comparable (public) transportation methods were analyzed. These were: the metro system, airplane / airport and the Channel Tunnel which connects France and England. From this, it was found that all three transportation methods use quite different boarding security measures. A combination of measures from different systems is wanted to optimize the security system for the Hyperloop transportation method.

Since the Hyperloop is still in concept stage, its design is not yet specified. Therefore, a specific version of the Hyperloop was assumed in this report. For this design, the key features are the following. The Hyperloop tube, through which the pods travel, is placed above ground level. Because the Hyperloop's vision is to be able to be used as daily transport (e.g. as commuting transport), it has been decided that the system will not be reservation-based. As a result of this decision, frequent arrival and departure of pods contributes to user experience; smaller pods, of approximately 20 people each, can be used to reach the same strived hourly passenger flow. For these smaller pods, a gate-type boarding system is used. This re-pressurizes a certain part of the Hyperloop vacuum tube to atmospheric pressure, so boarding is possible. Because of the smaller pods, this re-pressurization time is relatively short (~ 380 s).

For this system, the main risks that could be present are found to be hijacks and bombings. This was derived from statistical data considering airplane flights.

Limiting factors of the system had to be considered. These factors were: costs, time delays and regional differences from international travel. The additional costs, introduced by the boarding security system, turned out to be small compared to the expected ticket prices. Time delays were found to be best minimized, where possible. The regional differences have a large impact on needed boarding security. The correctly chosen boarding security system for the region (Hyperloop station) at issue, can be the right compromise between travel flow and boarding security for that particular case.

From this, two options of the Hyperloop boarding security system were derived.

- The first option is a security system which operates on a largely automated basis. This system is best applied in case the region's threat level is relatively low.

- The second option introduces a security system which involves a significantly larger amount of manual labor. This adds to overall security by double-checking risks with a second checking method (humans instead of machines). This system is best applied in regions where the threat level is relatively high

All Hyperloop stations are to be designed in such a way, that both options are possible. The chosen option at the time is based on the threat level at that particular time.

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