Pedestrian Flow Simulation and Capacity Analysis of Stations for Ultra-High-Speed Ground Transportation (Hyperloop)

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Abstract—**Hyperloop, as long-distance transportation, is competitive with high-speed rail (HSR) and aviation. With the concepts of magnetic levitation and low-pressure environments, the hyperloop can take passengers to their destinations faster in a more environmentally friendly way compared with existing ground transportation and aircraft. Currently, various research exists focusing on the passenger capacity of the entire hyperloop system and the comparison with other transportation modes, but the analysis of the hyperloop station design and its impact on the passenger flow conditions is rare. Therefore, this study aims to provide a comprehensive analytical process to assess passenger flow at hyperloop stations with the consideration of the special characteristics of the hyperloop system, such as the airlock process. This study assumes six scenarios with different station layouts and system configurations and constructs the models of these scenarios in PTV Vissim. Several indicators are introduced to evaluate the passenger flow conditions of each station scenario. Furthermore, this study defines a process to detect potential bottlenecks based on the concept of level of service (LOS). A sensitivity analysis is performed for each scenario with different peak hour factors (PHFs) and the simulation results of the different scenarios are evaluated. The Evaluation showed that the station with platform function separation had the best performance on the average travel time of passengers and LOS assessment. The analytical process in this study can also serve as a basic design reference for relevant agencies to assess passenger flow and improve bottleneck situations at future hyperloop stations.**

Keywords—Pedestrian Flow Simulation, Station Design, Hyperloop, Capacity Analysis

I. Motivation

With the advancement of technology and the increase in travel demand, the ever-changing transportations offer passengers more options to get to their destinations quickly and safely. Ultra-high-speed ground transportation, also known as hyperloop, is one of the new transportation concepts that has great potential advantages compared to existing transportation modes, such as aviation and high-speed rail (HSR). In the first published report on hyperloop [1] this new transportation mode is described as using the technology of magnetic levitation and low-pressure tubes to reduce the effects of friction and air resistance, thereby running at a higher speed but at a lower cost than other alternative transportation modes.

In addition to providing passengers with an experience of shorter travel time and a safer journey onboard, a complete public transportation system also requires a supporting design in its infrastructure. Stations are one of the important components of the transportation system. Compared to HSR and other railway system stations, additional boarding gates need to be installed at hyperloop stations to separate the platform area from the tube due to the pressure difference. Besides, each tube in hyperloop stations requires one or several airlock chambers for pressurization and decompression procedures to balance the pressure difference or establish a low-pressure environment. These processes may make the design of hyperloop stations different from other railway systems, affecting the passenger routes, passenger behaviors, boarding and alighting processes, and so on.

Overcrowding may occur and even cause severe congestion in stations when passengers encounter narrow passages or low-throughput facilities such as ticket gates and escalators, which are considered potential bottlenecks. [2] indicated that bottlenecks can lead to reduced flow efficiency, reduced passenger comfort, and even serious accidents in metro stations. As for aviation, [3] conducted the simulation and focused on identifying and suppressing the bottlenecks in an airport terminal. These studies all pointed out the importance of bottleneck detection in transportation hubs. These bottlenecks may also occur in hyperloop stations, and therefore need to be identified.

To detect the potential bottlenecks in stations, pedestrian level of service (PLOS) is a general criterion to determine the conditions of a specific area or the performance of the overall system. By calculating the certain attributes of the target area over a defined time interval, the level of service (LOS) can be confirmed by the thresholds of each level. Besides, If LOS is applied in the simulation, more accurate and realistic information can be obtained. [4] used the pedestrian simulation software PTV Viswalk to simulate the movement of pedestrians and applied LOS to compare the conditions of different scenarios. Their study implied that the application of the LOS standard together with the micro-pedestrian simulation tools was very helpful for analyzing the conditions of the infrastructure and providing the relevant authorities with clearer insights into facility design.

While there is extensive literature looking into passenger simulation, bottlenecks, and the LOS in the existing stations and terminals, similar analyses for hyperloop systems are rare. Therefore, this study aims to explore the passenger flow and LOS of hyperloop stations in different station designs during peak hours and to identify the potential bottlenecks in these conceptual hyperloop stations. To achieve the goals, this study first reviewed the literature related to hyperloop system design, commercial operations, and traditional train station design to give a reference guideline for building possible hyperloop stations. For the methodology section, the

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operational flow chart of the hyperloop stations was assumed and a new process was introduced to identify the low level of LOS as bottlenecks by considering the walking speed and experienced density of each passenger. To understand the impact of hyperloop station design on the passenger flow, this study proposed several hyperloop stations and used the simulation software PTV Vissim to perform the microscopic passenger simulation based on these conceptual stations. A sensitivity analysis of passenger demand and passenger travel time was conducted beforehand to explore the maximum simulation capacity limit of the stations. Furthermore, several important indicators of the simulation output such as passenger travel time, time spent at the low level of LOS, etc. were used to determine the performance of different station scenarios. The results of these scenarios were compared with each other afterward to find the optimal configuration among these hyperloop station designs proposed in this study. In the end, this paper summarized the characteristics of different hyperloop station scenarios and provided hyperloop developers and related authorities with a clear reference for station design regarding the features of hyperloop systems.

II. HYPERLOOP OPERATION AND STATION DESIGN

Several pieces of literature focused on the system operation of the hyperloop. Regarding the design of the hyperloop pod, [1] described two versions, which were differentiated by the functions of passenger-only capsules and passenger-plus-vehicle capsules. Equipped with the compressor fan, compressor motor, batteries, and seats, each passenger-only capsule could accommodate 28 passengers. Besides, according to [1], each pod could operate at a speed of 1220 km/h with an average departure time of 2 minutes, which allowed the total capacity of a single track to reach 840 passengers per hour. Meanwhile, [5] has visualized a futuristic concept for hyperloop pods, stations, and infrastructure. In this envision, several pods could form a convoy to provide more line capacity, and each pod in the same convoy would follow the preceding pod within a certain distance and adjust its speed automatically and simultaneously. In addition, pods within the same convoy but with different destinations could be separated when the convoy approaches the diverging junction, allowing the hyperloop system to have more flexible pod scheduling.

Due to the pressure difference between the inside of the tube and the station platform, the pressurization and decompression procedures are necessary and require the installation of airlocks or additional chambers in the branch section of the tube in the station. This airlock design has been introduced in many studies. [1] mentioned that there were two airlock chambers at the hyperloop terminal. Arriving capsules first entered the incoming airlock for the pressurization procedure. After the pressure in this airlock was the same as in the station, the capsules were able to enter the station for the alighting process. On the other hand, after all the passengers were aboard, the departing capsules went to the second airlock chamber for the depressurization procedure and entered the main tube after the pressure in the exit airlock reached the low-pressure environment. [6] suggested the operation of double airlock chambers in the study, one for primary operation and one for backup. This double airlock design prevented the entire system from being disrupted when the main airlock was damaged. As for the airlock system proposed by [7], the airlock chambers were installed on the entrance and exit tracks of the station. The crane device would move the incoming pods from the main tube to the specific airlock for pressurization and move the outgoing pods from an already depressurized airlock to the main tube.

Considering the operational demand and capacity of hyperloop systems, the maximum hourly capacity can be determined by pod capacity and headway, which is the minimum time gap between two consecutive pods. [8] proposed two hyperloop operation methods, moving-block (MB) and virtual coupling (VC), to assess the headway of the pods. With the different combinations of system operations and the number of airlock chambers in stations, the average time headway for each scenario was derived concerning the safe braking distance. They concluded that the shortest average headway between two consecutive pods at stations was 128.96 seconds with the platooning operating mode and 135.03 seconds with the coupling/decoupling mode and the configuration of Fixed Magnetic Switching (FMS). [7] assumed the operational process of the hyper-loop systems and evaluated the feasibility of this new transportation mode from the perspectives of demand for capsules, investment, and system capacity. In this case study, the author proposed that the average handling time at the terminal stations could reach 429.01 seconds. Meanwhile, [9] applied a general formulation based on deceleration capacity and pod speed to calculate the minimum safe headway. By this formulation, the researcher indicated that the pod could come to a complete stop without crashing the pod ahead with a minimum safe headway of 80 seconds for the hyperloop system.

Regarding the design of hyperloop stations, there is currently no clear standard due to the limited technology and feasibility of hyperloop, but there are existing studies that have proposed hypothetical hyperloop stations. [10] introduced a comprehensive design guideline for an underground hyperloop station to improve pedestrian flow. In this report, the writer divided the design concept into four main sections, including signage, horizontal circulation, vertical circulation, and platform. In addition, the author built a hypothetical hyperloop station under the same circumstance as the existing train station to make a comparison, showing that while the hyperloop station had higher capacity than a normal station, it required fewer vertical devices and horizontal space. The author explained that the main reason for the results could be the more even passenger flow in the hyperloop station. [11] stated that public transport facilities were essential to the function and identity of a city and provided many sketches for the conception and design of the future hyperloop station from the perspectives of urban infrastructure and architecture. As for the hyperloop station types, [12] proposed terminal and intermediate stations with different air-tightness methods with the consideration of short travel time, pressure difference, and air tightness. Nevertheless, the author indicated that all these possible station types existed with some technical issues, and the corresponding solutions needed to be further elaborated.

Even though there is currently no commercial hyperloop station and related regulation, many manuals and guidelines of similar transportation modes are available, such as HSR and sub-way. These design regulations developed over the years can be used as a reference for the design of hyperloop stations. The report by [13] provided clear platform design criteria for the safe promotion and efficient operation of HSR service. Through this report, the detailed geometric design of the HSR platform, such as horizontal alignment, width calculation, etc.

can be obtained. As for the railway systems of European countries, in accordance with the regulations of the European Commission [14], they follow unified design standards, aiming to build a unified railway network and facilities throughout the EU. These regulations define the construction guidelines for different subsystems within the railway infrastructure, including disabled facilities, lighting devices, floor, and platform design, and so on. In order to successfully implement the construction in accordance with EU regulations, the European Railway Agency published a document [15] to supplement the content and implementation details of the regulations. Finally, the United Kingdom (UK) also has its own guidelines for the design of stations to list the factors and components that influence station construction. In this manual, the guidance of the station planning, and the various station elements were presented to gain a thorough understanding of the design process [16], [17].

III. Methodology

The focus of this study is on passenger flow at hyperloop stations. However, nowadays the related technologies of the hyperloop are still in the experimental stage, and there is no existing commercial hyperloop station and corresponding station design manual. Therefore, a hypothetical hyperloop station was built in this research based on concepts in the literature and current technology. Before building the simulation model, several assumptions were made in advance because a lot of characteristics and information about hyperloop systems remained unknown:

- While [1] and [18] mentioned the importance of security checks before boarding at airports, this procedure usually took a long time and certainly led to serious congestion. Therefore, this study excluded security checks and corresponding facilities.
- Some studies indicated that ticket machines and office locations were crucial. If the main passenger flow was not affected by the passenger flow to buy tickets and the waiting queues in front of ticket machines, it could be optimized by reducing cross-interference [19], [20].
- Some studies showed that operating acceleration and deceleration should not exceed 0.5G due to safety and passenger comfort issues [18], [21], [22]. Considering the reality and feasibility, this study assumed that the maximum pod acceleration and deceleration is 0.2 G.
- As envisioned by [5], this study assumed that a convoy consisting of several capsules was feasible.
- Numerous reports have indicated that hyperloop systems had a small pod capacity but very short headway [1], [7], [24].

With the assumed pod capacity and headway in this study, the maximum line capacity of the hyperloop system could be calculated. One big capsule convoy contained 6 pods, each with 30 seats, thus there were 180 seats for a big capsule convoy. The headway for big capsule convoys was 3 minutes, so the maximum line capacity of big capsule convoys in each tube was 3,600 passengers per hour. For the layout of the base scenario, there were two tubes in each direction in the station, which meant that the maximum line capacity in each direction could reach 7,200 passengers per hour, and 14,440 passengers per hour for both directions. Also, the maximum line capacity of small capsule convoys (10 pods, each with 12 seats) was

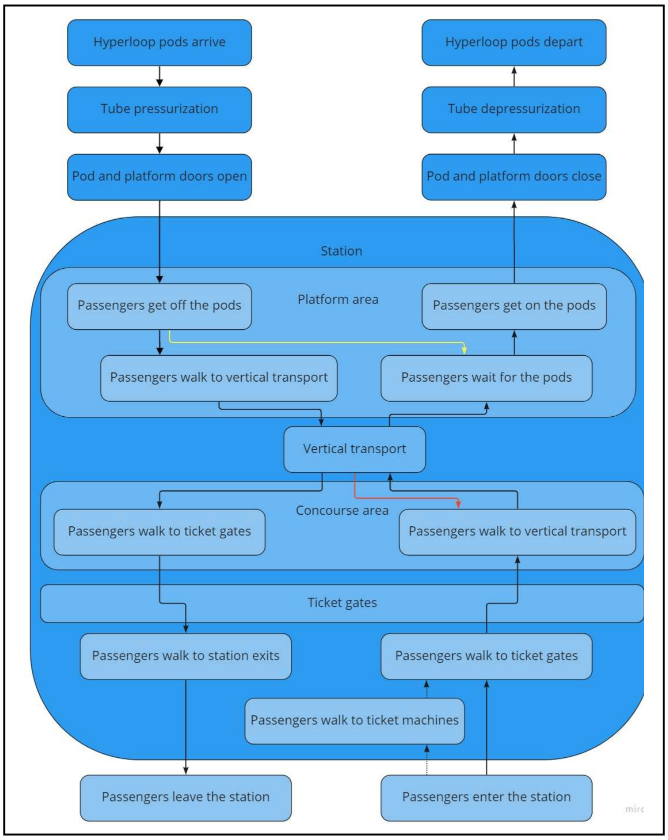

Fig 1. Inbound and outbound passenger flow at the station.

calculated by the same principle, but the headway changed to 2 minutes. The calculation also equaled 7,200 passengers per hour. Therefore, regardless of the type of capsule convoys, the base scenario of the hyperloop station in this study needed to accommodate at most 14,400 passengers per hour.

As for passenger demand, this study applied the principle of the peak hour factor (PHF) proposed by the Transportation Research Board [25] and calculated the design passenger capacity as the passenger demand. PHF was used to adjust the design passenger capacity from the maximum line capacity. If the design passenger capacity was close to the maximum line capacity, severe passenger congestion may occur because the system could not handle the uneven demand during peak hours. The design passenger capacity is defined as $P = P_m(PHF)$ where P is the design passenger capacity; P_m represents the maximum line capacity, which was 14,400 passengers in both directions per hour in this study; PHF stands for the peak hour factor, which was used in the sensitivity analysis in the range of 0.5 to 0.9.

After confirming all assumed parameters, a simple two-floor hyperloop station was constructed in PTV Vissim for a subsequent passenger flow simulation and evaluation. The whole process for system operation and the passenger flow in this system can refer to Figure 1.

IV. Scenario Design

For the different evaluated scenarios, different station designs were conceptually proposed by this study or referred to existing railway systems in order to find the relatively optimal station layout. This study applied the regulations from the California High-Speed Rail Authority [13] and the European Railway Agency [15] for the construction of concourse and platform areas, as these passenger movement areas had similar design principles, depending on passenger demand and flow conditions. As for flow rate and direction, a simple two-story hyperloop station was constructed in this study to avoid severe flow conflict. For the design of vertical transportation, this study followed the recommendations proposed by [10]. The author explained that the vertical circulation in this hyperloop station design manual was based on passenger demand and the flow rate on these infrastructures. Finally, the characteristics and the number of ticket gates in this research referred to the studies that compared different types of ticket gates and focused on the effects of the geometric design of ticket gates [10], [22]. The following six station designs were used in the simulations:

- Base scenario (Scenario 0): Figure 2 shows the base scenario in this study. There were two floors in the station. On the first floor, a station hall (concourse) with a length and width of 100 and 50 meters was constructed to accommodate incoming and outgoing passengers. There were entrances and exits on the top (north) and bottom (south) of the station hall, and each entrance and exit had several ticket gates respectively according to the passenger flow demand assumed in this study. On the second floor, there were two platforms with a length and width of 150 and 15 meters based on the convoy length and the minimum safety design width defined in the platform guidelines [15]. Each platform was equipped with one elevator, one staircase, and four escalators, two going down and two going up. Finally, there were a total of four hyperloop tubes next to these two platforms, and every two tubes were responsible for a travel direction.
- Scenario 1: Based on the base scenario but with platform function separation with three alighting platforms.
- Scenario 2: Platform function separation with three boarding platforms (with reversed platform function).
- Scenario 3: Ticket gates directly at the boarding platform with waiting areas in front of the pods.
- Scenario 4: Small capsule convoys (Scenario 0, but with 10 small pods with 12 seats forming a convoy).
- Scenario 5: Short platform (4 shorter platforms (80 m) with space for only 3 pods).

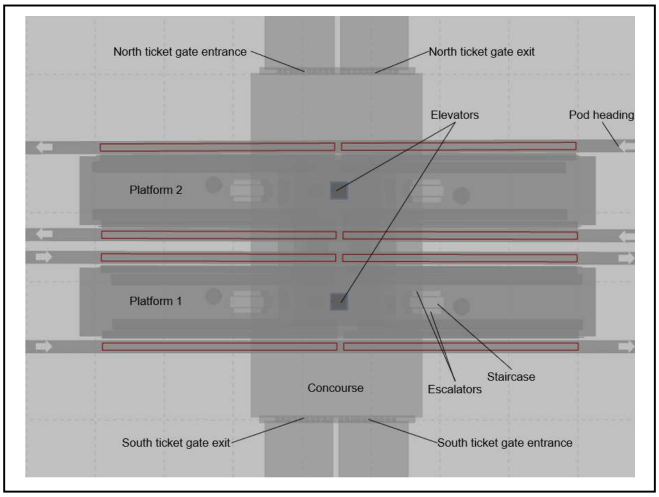

Fig 2. Station layout for the base scenario (scenario 0).

V. RESULTS

Based on the formula proposed by [26] and [27], this study determined the number of ten necessary simulation runs with different random seeds by using the mean and standard deviation of the average passenger travel time (1% of error allowable and t(9,0.95)). The average passenger travel time included inbound and outbound passengers. All attribute values were averaged from the results of those ten simulation runs, and the PHF value was set to 0.9 based on the sensitivity analysis in this study to avoid severe congestion. The passenger demand in each direction was fixed at 6,480 passengers per peak hour.

The "pedestrian grid cells" function was used to record the attributes of each small square within the station. Afterwards, the heat maps for experienced density and walking speed were to determine all possible bottleneck locations. In particular, this study used the passenger experienced density and the passenger walking speed as indicators. The experienced density represented the density perception of passengers. In the Vissim model, each passenger perceived the density within a radius of one meter at each time step, which defines the experienced density. For the evaluation of passenger experienced density, the average experienced density of 1 hour and the maximum experienced density of 10 seconds were applied to determine the passenger flow situation from both long-term and short-term perspectives. Additionally, also the passenger walking speed was evaluated in the same way.

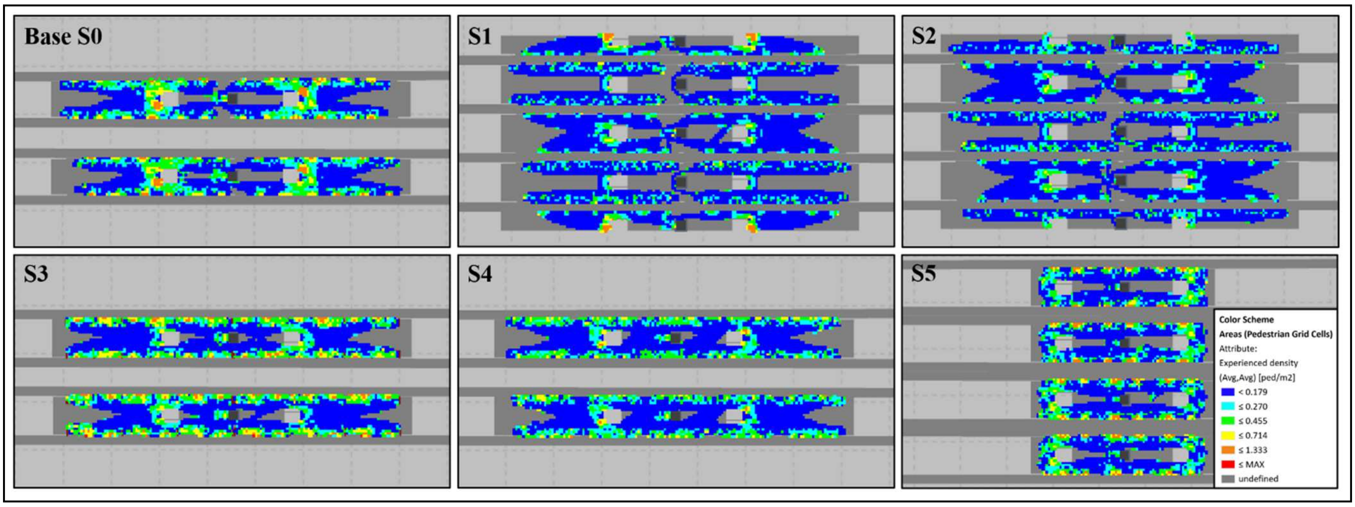

Fig 3. Comparison of the average density (over 10 simulation runs) on the second floor (with platforms) between all 6 different scenarios.

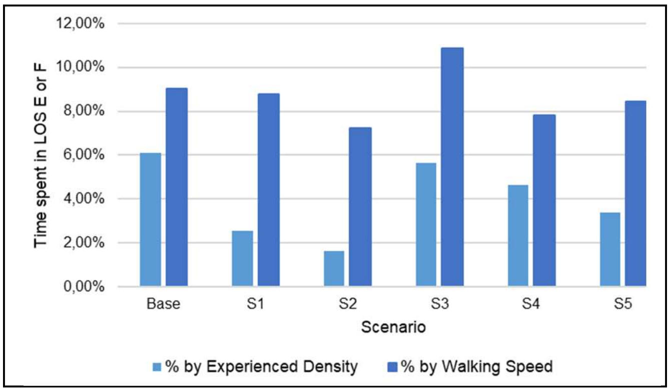

Fig 4. Percentage of time spent in LOS E or F by different attributes.

Figure 3 shows the average experienced density at the station. In the base scenario, passengers might experience high density near the escalators due to the limited walking space and throughput. The situation was more severe with sudden and dense passenger flow when the convoy entered the station. In addition, some dense conditions were found near the boarding gates because when the pod door was open, there was a conflict between alighting and boarding passengers, even with the rule of alighting first. In the long run, i.e., one hour, there was no LOS F situation (dark red area) in the station based on the average experienced density.

For scenario 1 with three alighting platforms, the dense passenger flow near the vertical transportation and boarding gates was improved due to the separation of boarding and alighting passengers compared to the base scenario. Congestion in the corridor between the escalators and the tubes on the platform was also less severe as the flow direction became more consistent.

In scenario 2 with three boarding platforms, the overall experienced density was improved further for both long-term and short-term periods. Although there was slight congestion in front of the exit gates, it was much relieved compared to scenario 1 because passengers disembarking from the 2nd and 4th platforms had enough space to walk to the queue and did not conflict with the queue. Furthermore, island platforms were provided for alighting passengers instead of side platforms, which could handle denser and sudden passenger flow when a large number of arriving passengers were entering the station concourse.

For scenario 3 the inbound and outbound ticket gates were moved to the position in front of each boarding gate on the second floor. The great improvement on the first floor could be found because passengers no longer stopped to validate their tickets when entering the station concourse. As for the second floor, both the average and maximum experienced density of the staircase and escalator entrances to the first floor were improved. Instead, high passenger densities were observed in each boarding waiting room and disembarking arrival room because all passengers were restricted in certain areas for boarding and alighting rather than distributed on the platforms in this scenario.

Regarding scenario 4 with small capsule convoys, the improvement of both average and maximum walking speeds on the platforms could be found compared to the base scenario. The decrease in the total number of passengers in a single convoy was the main reason for the improvement, so that passengers would feel less crowded on the platforms. In addition, the vertical transportation on the platforms, such as escalators, did not need to handle as many passengers in a short period as in the base scenario. Therefore, the average and maximum walking speeds at the entrances of the stairs and escalators were also improved compared to the base scenario.

Finally, with the short platform design in scenario 5, because both inbound and outbound passengers were distributed to more platforms, the high passenger density near the entrances of the vertical transportation on the platforms was alleviated compared to the base scenario.

Based on the average and maximum density as well as the average and minimum walking speed, the LOS was also determined for each of the scenarios for every second. As described in Table I, passengers were considered to be in LOS E or F if the experienced density was above 0.71 passengers per square meter. As for the walking speed, when a passenger changed the walking direction, the level of walking speed dropped to LOS E easily even though there was no congestion. Therefore, a stricter standard (LOS F) was used for walking speed to exclude the cases where the walking speed dropped temporarily due to direction changes, which meant that passengers were considered to be in LOS F if the walking speed was below 0.87 meters per second. If the walking speed was lower than this value, as observed in the simulation, passengers may be experiencing severe congestion, conflicts with other passengers, or queuing, some of which cannot be detected using only experienced density.

TABLE I. PEDESTRIAN LOS DEFINITION IN THE HCM [28].

LOS	***Definition***	***Ped. Space (m^2/pax)***	***Density (pax/m^2)***	***Speed (m/s)***
A	Free circulation zone	≥5.6	≤0.18	≥1.48
B	Restricted circulation zone	3.7-5.6	0.18-0.27	1.45-1.48
C	Personal comfort zone	2.2-3.7	0.27-0.45	1.39-1.45
D	No touch zone	1.4-2.2	0.45-0.71	1.31-1.39
E	**Touch zone**	**0.75-1.4**	**0.71-1.3**	0.87-1.31
F	The body ellipse	≤0.75	≥1.3	**≤0.87**

Vissim can record each passenger's walking speed and experienced density every second. Figure 4 shows the percentage of time spent by passengers in LOS E or F determined by walking speed and experienced density. It can be observed that the influence of walking speed was higher than the experienced density for all scenarios. Compared with the base scenario, all other scenarios improved the experienced density situations. Among these scenarios, the experienced density for scenarios 1 and 2 was significantly improved due to flow separation on the platforms. Secondly, in scenarios 4 and 5, because the passenger load on each platform became smaller, the percentage of LOS E or F in the experienced density in these two scenarios also decreases. As for scenario 3, although the experienced density was improved, the effect was not obvious because passengers were restricted to smaller areas for boarding and alighting.

VI. CONCLUSIONS

This study designed several possible hyperloop stations to analyze the passenger flow conditions and compared these scenarios to find suitable station layouts to avoid bottlenecks and congestion. It could be observed that the entrances and exits of ticket gates and vertical transportation, such as escalators and stairs, were the potential bottlenecks for each proposed station layout in this study. Although every proposed hyperloop station in this study detected the bottlenecks, some designs and configurations could reduce the severity of the congestion generated by these bottlenecks. Thus, this paper employed two main indicators to evaluate the performance of each station scenario, namely the average travel time of passengers and the percentage of time spent by passengers spend in low LOS.

From the perspective of the average travel time, scenario 2 with three boarding platforms and two alighting platforms had a great performance at any PHF value tested in this study, i.e., from 0.5 to 0.9, because there were fewer flow conflicts on the platforms and all escalators could run in the same direction to increase passenger throughput and reduce passenger waiting time for riding escalators. As for scenario 3, where the ticket gates were installed on the platforms, although boarding passengers had the shortest travel time, the alighting passengers experienced much longer travel times due to low utilization of each exit ticket gate, resulting in the worst overall average travel time of passengers.

Through the further attribute analysis of LOS, it was found that the LOS performance in scenario 2 was much improved because the passenger experience density became relatively low compared to the base scenario. As for scenario 3, the percentage of low LOS caused by passenger experience density was similar to the base scenario. On the other hand, the low LOS due to passenger walking speed was improved significantly in scenario 2 compared to the base scenario, but the improvement of low LOS caused by the passenger walking speed in scenario 3 was not obvious.

The results of the motion analysis of LOS showed that scenario 2 had the best LOS improvement because passengers experienced significantly less low LOS in the motions of "Waiting or approaching PT" and "Escalator and stairs-related". The LOS performance in scenario 3 was even worse than in the base scenario, as alighting passengers spend more time queuing in front of exit ticket gates in the arrival rooms.

In this study, scenario 2 with three boarding platforms and two alighting platforms had advantages in both evaluation indicators. Therefore, based on the perspectives of average passenger travel time and low LOS experience, this study suggested that the station layout with platform function separation could be applied in the future hyperloop station to avoid bottlenecks and passenger congestion. Besides, this study provided the comparisons of different station layouts and system configurations. For instance, the scenario with small capsule convoys had better performance in terms of average travel time and low LOS experience compared to the configuration of big capsule convoys; the scenario with short platforms outperformed the base scenario on these two indicators. With further development through validation and calibration, the analytical process presented in this study could become an effective tool for hyperloop researchers and relevant authorities to assess passenger flow conditions and detect potential bottlenecks in future hyperloop stations.

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