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MANAGEMENT OF GOODS FLOW IN HYPERLOOP TRANSPORTATION SYSTEM

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Purpose: The purpose of this study is to analyze the Hyperloop system in terms of freight transportation management, aiming to improve the efficiency of cargo transport while supporting sustainable development goals. The research evaluates material flow and simulation processes to highlight the advantages of Hyperloop over existing transportation modes.
Design/methodology/approach: the study employs advanced simulation tools such as FlexSim and Archicad, commonly used in design and logistics analysis. These tools enabled precise modeling and in-depth analysis of the Hyperloop transportation system, focusing on operational efficiency and identifying potential bottlenecks.
Findings: The results demonstrate that the Hyperloop system can simultaneously handle both passengers and cargo according to a predefined schedule. The simulation model revealed the system's capacity, the load on the logistics infrastructure, the integration of passenger and cargo traffic and the key challenges associated with coordinating these flows to minimize potential downtime.
Research limitations/implications: while the study provides a comprehensive framework for analyzing the Hyperloop system, it is limited to simulation-based analyses. Future research could include real-world testing and broader integration of various environmental and economic factors.
Practical implications: The findings of the study provide practical insights for the implementation of Hyperloop technology in logistics and freight transport. They form a foundation for stakeholders to design efficient, sustainable and reliable transportation systems.
Originality/value: This study contributes to the development of Hyperloop technology, highlights its potential to revolutionize freight logistics and provides a methodological framework for future development and research in this field.
Keywords: Hyperloop, cargo transport, cargo flow management, transport efficiency, logistics.
Category of the paper: Research paper.

1. Introduction

The dynamic technological development observed in recent decades responds to the growing needs associated with globalization, urbanization, and increasing demands for speed and efficiency in transportation processes (Guerrero-Ibáñez et al., 2012). In the face of challenges such as congestion in traditional transportation systems and the need to reduce greenhouse gas emissions, the Hyperloop concept has gained particular attention. This innovative transportation system is designed to enable fast, efficient, and eco-friendly movement of both passengers and cargo (Musk, 2013; Ross, 2015). The technology, based on the use of low-pressure tubes and capsules traveling at speeds exceeding 1000 km/h, addresses contemporary challenges in transportation and logistics (TÜV SÜD, 2019).

The efficiency of transportation systems is a critical factor in enhancing the competitiveness of national economies and global supply chains (Porter, 2008). Fast and reliable transportation helps reduce operational costs, improve market accessibility, and increase business flexibility (Rodrigue, 2020). In this context, Hyperloop offers the potential to shorten delivery times and introduce new opportunities for optimizing goods flow by integrating modern technology with existing logistics networks. With its low energy consumption and reduction of carbon dioxide emissions, this system has the potential to set new standards for sustainable transportation (Gkoumas, 2021).

Existing research on Hyperloop technology has primarily focused on technical and engineering aspects, such as infrastructure design, motion dynamics, and energy efficiency. A wealth of important data have been provided in this area, confirming the system's potential and feasibility. However, issues related to managing goods flow within the system, including identifying bottlenecks, forecasting demand, and integrating with existing logistics structures, remain insufficiently explored. Effective management requires a comprehensive approach that considers both technical constraints and operational and economic requirements (Werner et al., 2016).

This study focuses exclusively on freight transportation, with particular emphasis on managing the flow of goods within the Hyperloop transportation system. The research aims to identify key operational challenges, evaluate the system's efficiency, and develop recommendations for its future implementation. The analysis provides both practical and theoretical insights for further research and practical implementation efforts in the Hyperloop domain.

2. Literature review

The Hyperloop system is characterized by the use of innovative solutions in the field of transportation, utilizing advanced technologies in near-vacuum conditions. The core component is the capsule, which will travel through tubes with near-vacuum pressure. High speeds will be achievable through the application of a Linear Induction Motor (LIM) and magnetic levitation technology. Additionally, appropriate analyses have been conducted to find the optimal aerodynamic shape of the vehicle, minimizing air resistance that would hinder the achievement of high speeds (Braun et al., 2018; Abdelrahman et al., 2017). Hyperloop capsules are designed for both passenger and freight transport, with significant differences in vehicle construction depending on their intended purpose (Mitropoulos et al., 2021; Opgenoord et al., 2018).

Freight transport capsules feature a simplified internal structure divided into three segments. In the central part, instead of seats, there will be space designated for containers carrying cargo. The vehicle design will accommodate the transport of materials with small or medium dimensions, with a total weight not exceeding 2500 kg (Hyperloop TT, 2023; Nøland, 2021).

Unlike passenger capsules, which are equipped with seating and amenities for travelers, freight capsules focus on maximizing the use of available space. The capsule design incorporates all subsystems, such as propulsion, levitation, and safety systems, which remain identical for both passenger and freight versions (Hardt Hyperloop, 2023; Rodrigue, 2020).

One of the advantages of Hyperloop technology is its ability to utilize existing tube infrastructure for both passenger and freight transport according to a set schedule. This means there is no need to build a separate network for freight transportation, leading to significant cost savings (Mitchell et al., 2010; Hansen, 2020). Freight movement will occur both during the day, alongside passenger traffic, and at night when passenger capsule frequency decreases. During off-peak hours, freight transport capacity can be increased according to demand. The implementation of Hyperloop technology for goods transport represents a significant milestone in improving a country's economic performance and reducing transportation time for specific goods, particularly those requiring rapid delivery, such as medical supplies, food or high-value products (Polak, 2017; Guo et al., 2022).

The application of Hyperloop technology will serve as the foundation for future sustainable transportation systems. Examples of such implementations include the transportation of goods across distant regions at speeds comparable to air travel but with significantly lower costs and a reduced environmental impact (Hyperloop Development Program, 2022).

However, Hyperloop technology requires the development of an advanced transportation system and comprehensive solutions to ensure the safety and efficiency of both passenger and freight transport. The infrastructure includes key components such as transport tubes, passenger and freight stations. Capsules will travel through special tubes with near-vacuum pressure, which, in the original concept, are supported by concrete pylons. Photovoltaic panels are planned for installation on top of the tubes to capture solar energy for powering the system. This approach aims to reduce infrastructure maintenance costs and contribute to the environmental sustainability of the transportation system. Alternative configurations include placing transport tubes at ground level or in underground tunnels, similar to metro infrastructure. However, due to the desire to reduce costs associated with land acquisition or the relocation of residents along the planned route, the constructing the Hyperloop system on concrete pylons is considered an efficient solution. The tube diameter is expected to range from 3.3 to 4.3 meters and the tubes will be made of steel, ensuring durability and system integrity. The material will be selected to withstand unforeseen weather events, such as floods or tornadoes (Musk, 2013; Rümeysa et al., 2021).

Furthermore, the infrastructure of the Hyperloop freight station should facilitate the efficient flow of goods. A critical factor in the functionality of the freight station is the minimization of downtime and the elimination of potential delays in cargo transportation. Leading institutions involved in the development of the technology have proposed several designs for the freight station and its operational model. One concept suggests that goods will be delivered to a warehouse at the Hyperloop station and then shipped during the night to the destination station. At the destination, the cargo will be received by other carriers, such as trucks, and distributed to its final destination (Rudowski, 2018).

The American research company Hyperloop Transportation Technologies has presented the concept of a freight station known as HyperPort. In this design, containers carrying cargo would be transported above the Hyperloop tracks using cranes and then placed into capsules, which, once loaded, would depart for the destination (HyperPort cargo solution, 2021).

Holvad (2023) describes a scenario in which capsules are dispatched every 70 seconds, providing a capacity of 6 million tons per year, assuming each capsule can carry 10 tons of cargo. However, considering potential system maintenance and repairs, the realistically estimated amount of goods that can be transported is approximately 5.84 million tons.

Munir et al. (2019) assess the operation of the Hyperloop system in Germany over a distance of 300 km, which would allow freight speeds to increase to 1054 km/h, approximately 11 times higher compared to road transport. Factors associated with the implementation of the Hyperloop system, such as reduced operational costs, fuel savings and decreased road traffic, are expected to result in annual savings of approximately 163 million euros.

Freight transportation via the Hyperloop system could thus play a key role in the future of transport, combining speed, energy efficiency and minimal environmental impact (Nowak, Owczarek, 2020).

3. Materials and methods

The study focuses on analyzing the flow processes occurring at the freight station. The analysis of freight flow management includes developing the freight station layout using Archicad and importing the design into FlexSim for process simulation. This approach allowed for observing the Hyperloop system's operation and identifying areas requiring improvement. The actions taken aimed to streamline transport system processes and illustrate the functioning of the freight station.

3.1. Research tools

The primary tool employed in this study is FlexSim, a software that allows for the precise replication of processes occurring in a given system by creating flow logic. The use of FlexSim is justified by its versatile capabilities in modeling and simulating complex systems, which aligns perfectly with the intricate nature of the Hyperloop transportation system's development. FlexSim provides a powerful and user-friendly simulation environment that can support various stages of a project, enhancing efficiency and accuracy while aiding decision-making processes (Lewicki et al., 2024). The software enables the creation of detailed and realistic models of the entire Hyperloop infrastructure, including freight transport, storage and distribution. The study involves multiple interacting components and dynamic processes. FlexSim's advanced simulation features allow for the representation of time-dependent behaviors, facilitating the analysis of the system's responses to different scenarios and inputs. This enables the modeling of the complete Hyperloop system, analysis of factors such as traffic intensity and the identification of potential bottlenecks in the system (Rumin et al., 2023).

Figure 1 illustrates a diagram of the simulation model development process, reflecting the underlying processes and encompassing key stages from problem formulation to solution implementation. The process is divided into three main phases: conceptual, simulation modelling and model experimentation. The diagram begins with the formulation of the problem, which serves as the basis for setting modeling objectives. Next, the conceptual model is developed, creating a simplified representation of the real system. Concurrently, data collection and analysis activities are carried out to ensure model accuracy. FlexSim provides a user-friendly and intuitive interface, where model construction involves adding selected visual elements, linking them and assigning appropriate input data (Baggio et al., 2021; Blaut et al., 2024).

The next step is model translation, which involves converting the conceptual model into a simulation version. After the model is created, tests are conducted to verify its correctness. If the tests results are positive, the model undergoes validation to assess its credibility. Once validation is successful, the process advances to the experiment planning phase, followed by execution.

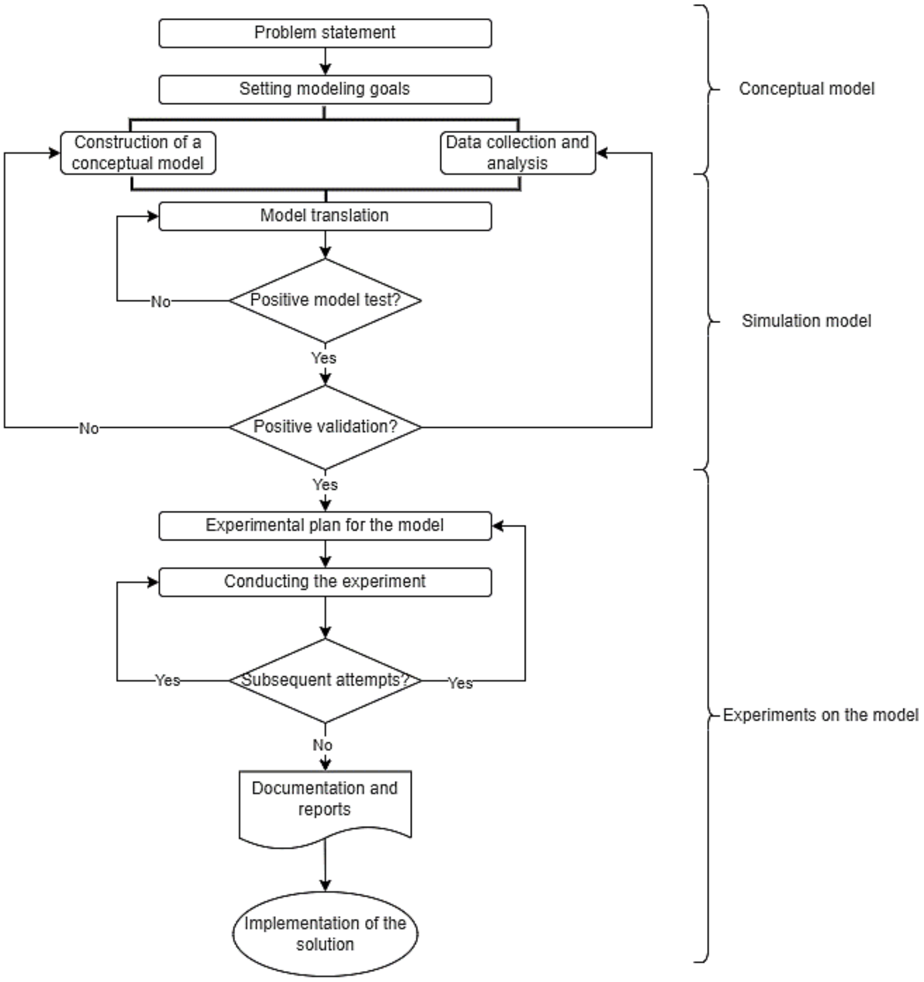


Figure 1. Diagram of the model building process.

Source: Own elaboration based on Karkula, 2013.

Simulation results are analyzed and additional trials may be conducted to optimize performance. The process concludes with documentation and report generation, summarizing the results and conclusions of the experiments. Finally, the solution is applied to the real system. The diagram emphasizes the iterative nature of the process, enabling continuous model refinement at each stage until optimal results are achieved (Hamdia et al., 2021).

Another tool used in this work is Archicad, which was employed to create the Hyperloop station model and plan the route to the station. The application of Archicad in the Hyperloop infrastructure development project leverages its exceptional capabilities in Building Information Modeling (BIM), providing a comprehensive collaboration platform for designing, visualizing, managing complex architectural and infrastructure projects. Archicad offers distinct advantages that address the intricate requirements of the project, enhancing collaboration, precision and efficiency during the planning and design phases. The key benefit of Archicad is its BIM- focused methodology, enabling the creation of an integrated and collaborative model for the entire Hyperloop infrastructure (Dallasega et al., 2023). This centralized platform facilitates seamless collaboration among architects, engineers and stakeholders, ensuring a synchronized approach to design and construction.

Furthermore, Archicad supports open BIM standards, enabling interoperability with other software tools used in the project, such as FloWorks and FlexSim. This ensures smooth data exchange across different project areas, maintaining accuracy and consistency throughout the process. Archicad's capabilities include generating detailed construction documentation, which is crucial for providing precise and comprehensive instructions for construction teams, ensuring that the Hyperloop infrastructure is built in compliance with the defined design, regulations and standards (Pękała, Stryhunivska, 2024). By utilizing advanced information management features, Archicad minimizes errors and streamlines communication between different design departments during the project creation phase. The software includes an extensive library of materials and visualization tools, supporting the design of complex structures and forms. This accelerates and simplifies model creation while optimizing spatial planning and solutions (Baporikar, 2024; Parekh, Trabucco, 2024).

3.2. Input data

The freight station has been designed to ensure efficient goods flow. It consists of two main sectors dedicated to managing incoming cargo. These areas, referred as 'Delivery of Goods', are located on both sides of the tracks along which the Hyperloop capsules move. A key component of the station's operation is a crane positioned at the capsule parking spots, designed for loading and unloading vehicles. A container storage area has also been included to allow containers to safely wait for subsequent stages of their journey to the destination. The layout and appearance of the freight station are illustrated in Figure 2.

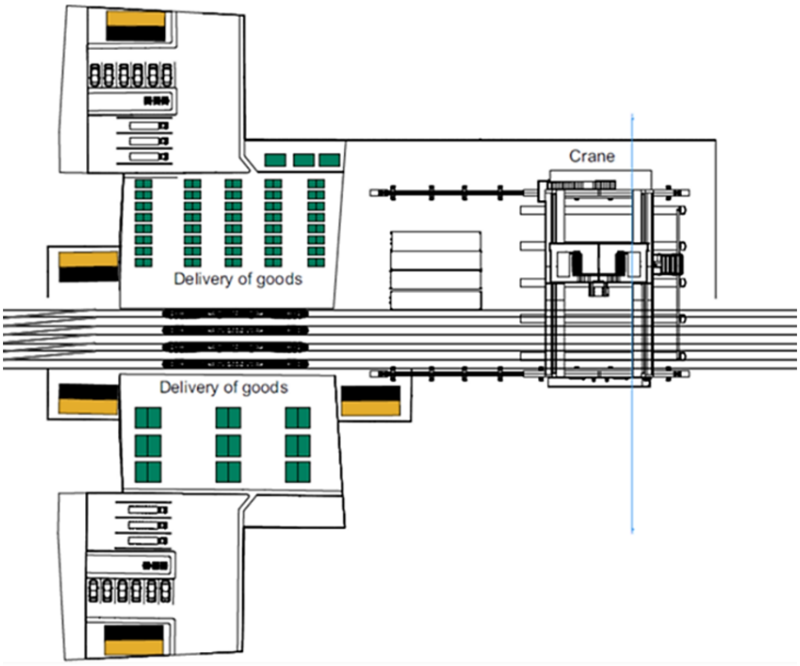


Figure 1. The layout of a cargo station.

Source: Own elaboration.

The central part of the freight station consists of tracks dedicated to vehicle movement. They are designed to ensure efficient transport of capsules to the destination station. In addition to cranes used for loading and unloading containers, autonomous guided vehicles (AGVs) will also be utilized to carry containers. These vehicles will transport goods between the warehouse and logistical operation areas located near the capsule. A 3D view of the freight station is presented in Figure 3.

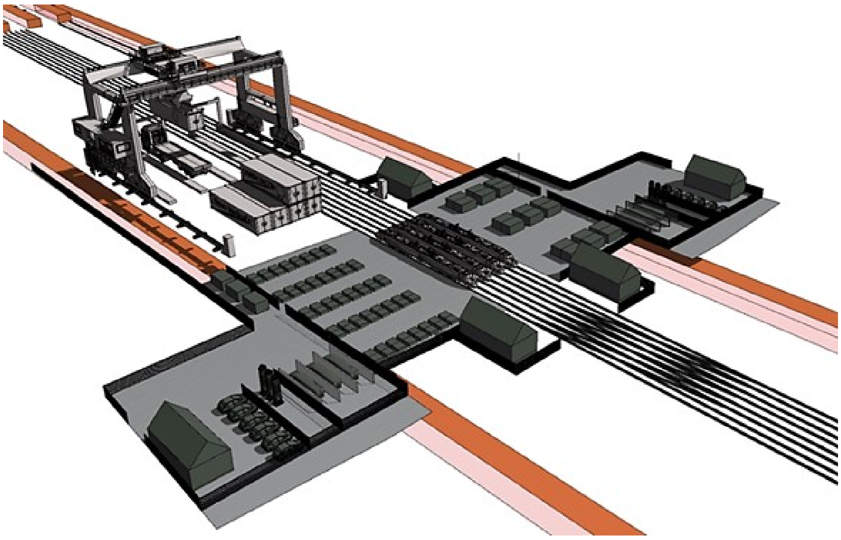


Figure 2. 3D model of a cargo station.

Source: Own elaboration.

Based on the Hyperloop freight station model created in Archicad, simulation processes were conducted using FlexSim. These processes are presented in a block diagram that reflects the operations at the station, as shown in Figure 4.

The simulation process was divided into two main paths: container handling and capsule servicing. The first simulation path focuses on container transportation. The primary criteria include the delivery time of the container to the freight station and the frequency of truck arrivals. Next, the time required for container inspection and labeling is considered, followed by placement in the warehouse after approval. The subsequent step involves sorting and arranging containers, followed by their transfer to autonomous AGVs using a crane. The loading time onto AGVs and their waiting time for further logistical operations are also taken into account.

In the next step, the transport time of containers to the loading area is analyzed, where they are transferred onto Hyperloop capsules using a crane. Before the capsule is dispatched, the time required for final inspection and documentation completion is taken into account. The loaded capsule is then directed to the airlock, where the air is evacuated from the tube-a process accounted for in the simulation. Once this procedure is completed, the capsule begins its journey to the destination. Simultaneously with the processes related to cargo reception at the warehouse, operations concerning the capsule's arrival at the station are conducted. Technical inspections of the capsule are performed at the primary Hyperloop vehicle inspection station, covering both periodic and additional technical checks.

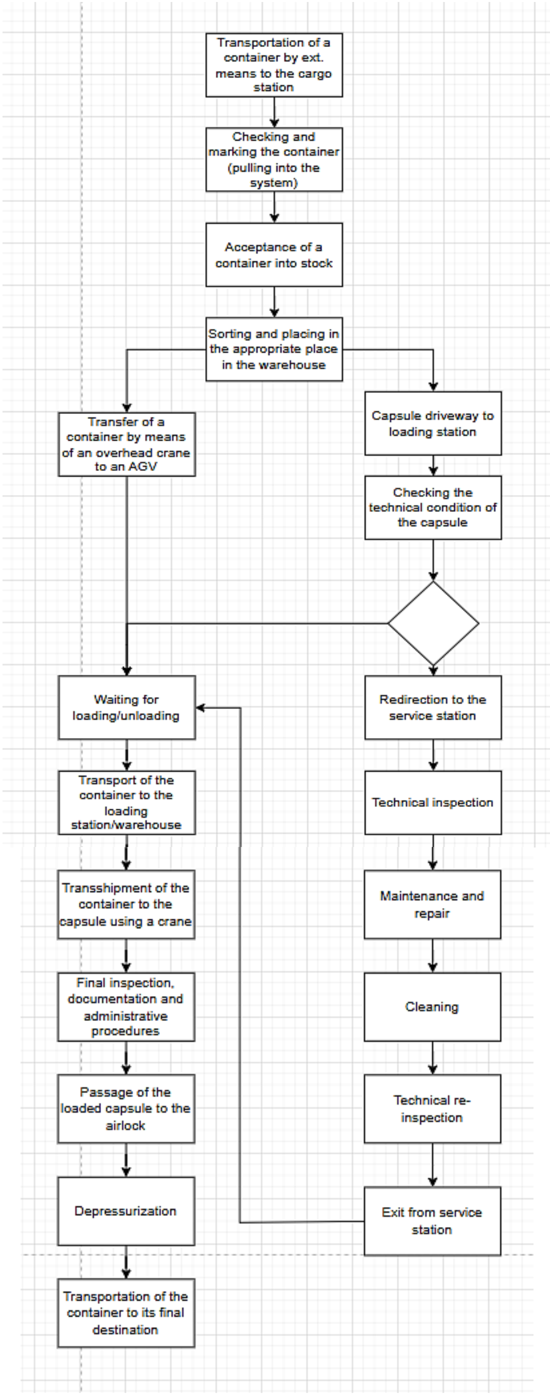


Figure 4. Block diagram of logistics processes taking place at a goods station.

Source: Own elaboration.

Before departure, the capsule undergoes a technical inspection to detect any potential faults and prevent issues during transit. If no repairs are needed, the capsule proceeds to the loading area, ensuring smooth operations during the journey. If repairs are necessary, the capsule is directed to the Hyperloop vehicle inspection station located within the freight station. The time required to direct the capsule to the inspection station is also accounted for. If defects are detected, the capsule is redirected to the service station. At the service station, a comprehensive technical inspection is conducted, including maintenance, repairs and cleaning of the capsule.

Once the service work is completed, the capsule undergoes a follow-up inspection. If no issues are found, the capsule leaves the service station and is ready for further use. The entire process, illustrated in Figure 4, highlights the key stages of container transport, logistics at the freight station and the comprehensive technical servicing of the Hyperloop capsule.

Before starting the simulation, the appropriate input data for the operations at the Hyperloop freight station were defined. This is a critical step to ensure accurate results and support further analysis of the system's performance. Examples of input data include the duration of specific loading and unloading operations of capsules, transport times between the warehouse and the crane and the speed of AGV movement. All parameters entered into the simulation model are summarized in Table 1.

Table 1.
Input data for a cargo station simulation

Cargo station		
Parameter	**Value**	**Unit**
Capsule acceleration	4,5	m/s^2
Velocity increment	222,22	m/s
Time to exit from the airlock	41,5	s
Time to pump out air in the airlock	60	s
Capsule transit time to the airlock	41,5	s
Time to load container onto capsule (crane transfers container)	120	s
Time to transport container AGV to loading station where the capsule is located	400	s
Distance from AGV cart pickup point to loading station	200	m
Loading/unloading procedure time from container arrival at warehouse to placement on AGV	1800	s
Distance capsule must travel to reach maximum velocity	10287	m
Safe AGV cart speed	2	m/s
Maximum speed	750	km/h

Source: Own elaboration.

Considering the actual operating conditions of the Hyperloop system, it should be assumed that freight capsules will travel on the same tracks as passenger capsules. Therefore, effective organization of both types of traffic is essential to ensure smooth and efficient operations. For this purpose, passenger traffic intensity was analyzed throughout the day. Based on a study conducted on the Nanjing metro, specific time periods for both passenger and freight traffic were identified. The simulation also accounted for peak hours in passenger transport. Figure 5 illustrates the distribution of passenger traffic intensity in the Nanjing metro over a 24-hour period, showing variations in passenger flow throughout the day (Yu et al., 2019).

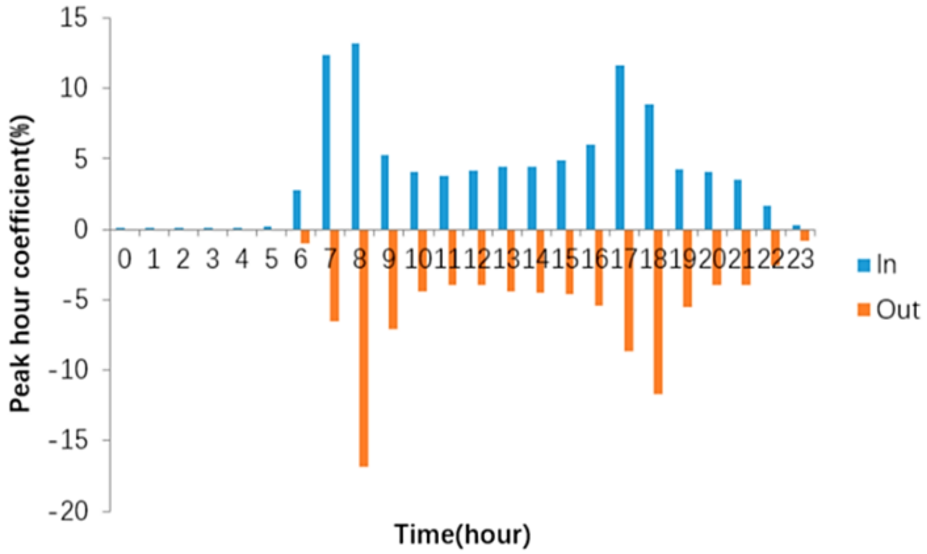


Figure 5. Distribution of passenger traffic in Nanjing metro area.

Source: Yu et al., 2019.

The horizontal axis represents the hours from 12 p.m. to 11 p.m., while the vertical axis shows the peak hour factor expressed as a percentage. The chart is divided into two categories: "In" and "Out." Blue bars represent entrances to the metro, labeled as "In," while orange bars represent exits from the metro, labeled as "Out." During the morning rush hour, between 7 a.m. and 9 a.m., there is a noticeable increase in the number of passengers entering the metro, as indicated by the blue bars rising above the horizontal axis. At the same time, there is a marked decrease in the orange bars, indicating that many people are exiting the metro as they reach their destinations, typical of commuting patterns to work or school. Another peak in traffic occurs in the afternoon and evening, between 5 p.m. and 7 p.m., when passengers once again enter the metro to return from work or other activities. During this period, the "In" factor increases, while the orange bars reflect a higher outflow of passengers leaving the system. Outside these peak hours, between 10 a.m. and 3 p.m. as well as from 8 p.m. to 11 p.m., the peak hour factor values are significantly lower and passenger traffic appears more balanced. No significant differences are observed between entrances and exits, indicating lower traffic intensity during non-peak hours.

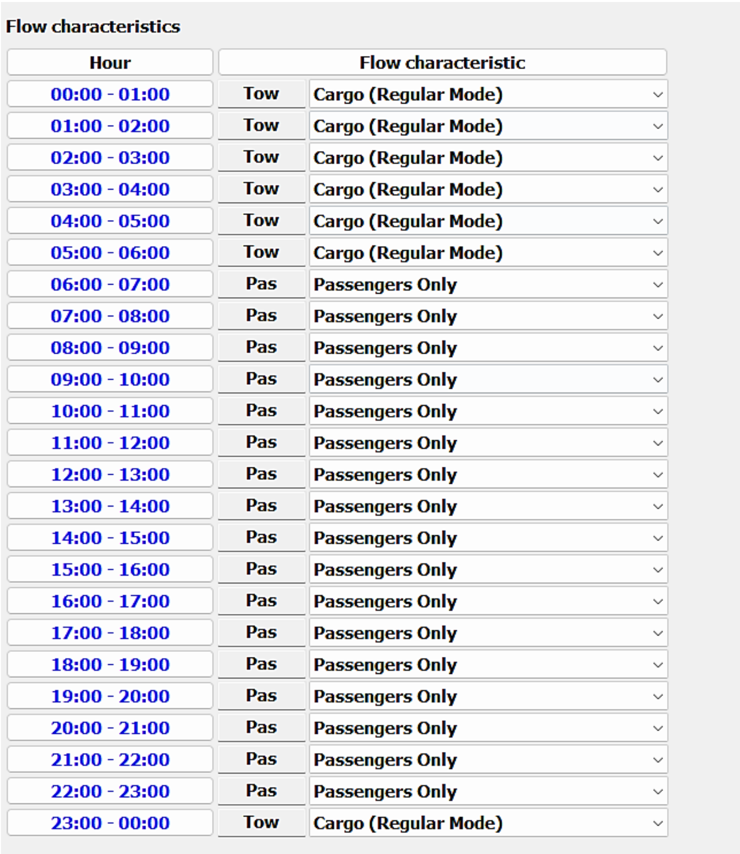
Based on the above analysis, the simulation model assumes that passenger traffic operates between 6:00 a.m. and 11:00 p.m., while the freight station operates from 11:00 p.m. to 6:00 a.m. This method of traffic organization helps avoid potential conflicts that may arise when both types of capsules travel simultaneously. An estimate of the number of freight capsules, determined by their dispatch frequency, is presented in Table 2.

Table 2.
Cargo station capacity.

Station operation		From 23:00	To 06:00
Capsule release frequency	Unit	Number of capsules per 1h	Number of capsules during station operation hours
10	s	360	1800
20	s	180	900
30	s	120	600
45	s	80	400
60	s	60	300
120	s	30	150

Source: Own elaboration.

The study assumes that freight traffic will take place between 11:00 p.m. and 6:00 a.m. The schedule for passenger and freight capsule movement is presented in Figure 6. This schedule also provides the flexibility to adjust time periods during which the traffic occurs, enabling the testing of different transportation organization scenarios.


Flow characteristics

Hour	Flow characteristic	
00:00 - 01:00	Tow	Cargo (Regular Mode)
01:00 - 02:00	Tow	Cargo (Regular Mode)
02:00 - 03:00	Tow	Cargo (Regular Mode)
03:00 - 04:00	Tow	Cargo (Regular Mode)
04:00 - 05:00	Tow	Cargo (Regular Mode)
05:00 - 06:00	Tow	Cargo (Regular Mode)
06:00 - 07:00	Pas	Passengers Only
07:00 - 08:00	Pas	Passengers Only
08:00 - 09:00	Pas	Passengers Only
09:00 - 10:00	Pas	Passengers Only
10:00 - 11:00	Pas	Passengers Only
11:00 - 12:00	Pas	Passengers Only
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18:00 - 19:00	Pas	Passengers Only
19:00 - 20:00	Pas	Passengers Only
20:00 - 21:00	Pas	Passengers Only
21:00 - 22:00	Pas	Passengers Only
22:00 - 23:00	Pas	Passengers Only
23:00 - 00:00	Tow	Cargo (Regular Mode)

Figure 6. Schedule of transport mode by simulation time period.

Source: Own elaboration.

The simulation model reflects the connections between seven key cities in Poland from both a logistics and economic perspective. These cities include Kraków, Katowice, Warszawa, the Transport Hub CPK in Baranów, Wrocław, Łódź and Gdańsk. The specific locations are presented in Figure 7.

Figure 7. Locations of the cities included in the simulation.

Source: Own elaboration.

4. Results

The simulation was conducted over a 24-hour period, allowing for the observation of the full system operation and the collection of final data related to infrastructure capacity. The results confirm the system's ability to handle a large number of passengers and freight containers, while accounting for infrastructure constraints and the traffic schedule. During the simulation, over 42,000 passengers were served, with the average capsule travel time of approximately 9000 seconds. This result highlights the potential for effective passenger flow management within the Hyperloop system. The travel time represents the average transport duration between all locations considered in the simulation. Additionally, during the freight traffic operation, 183 containers were transported, further demonstrating the system's cargo-handling capacity, which is a crucial aspect of its functionality. Figure 8 presents the simulation results regarding the performance of the Hyperloop transportation system over the analyzed period.

Total Number of Passengers Serviced per Day	42173.00
Minimum Loop Time [s]	7696.55
Maximum Loop Time [s]	10801.97
Average Loop Time [s]	9042.29
Delivered Containers	183.00

Figure 8. Analysis of simulation results.

Source: Own elaboration.

According to the simulation results, the shortest time required to complete a full cycle is 7696 seconds, while the maximum time reached 10800 seconds, which may indicate potential disruptions or system overloads at specific points. The average full cycle time is 9042 seconds, reflecting the standard cycle duration for most operations. The simulation results regarding the performance of the Hyperloop transportation system during the analyzed period confirm the system's efficiency in managing both passenger and freight transport. At the same time, the differences between the minimum, maximum and average full cycle times highlight areas that may require further investigation. These parameters can form the basis for additional analysis and optimization of the system's operation.

Additionally, the model also provides results illustrating the load at individual freight stations in terms of crane and autonomous guided vehicle utilization. These data for the Kraków station are presented in Figure 9.

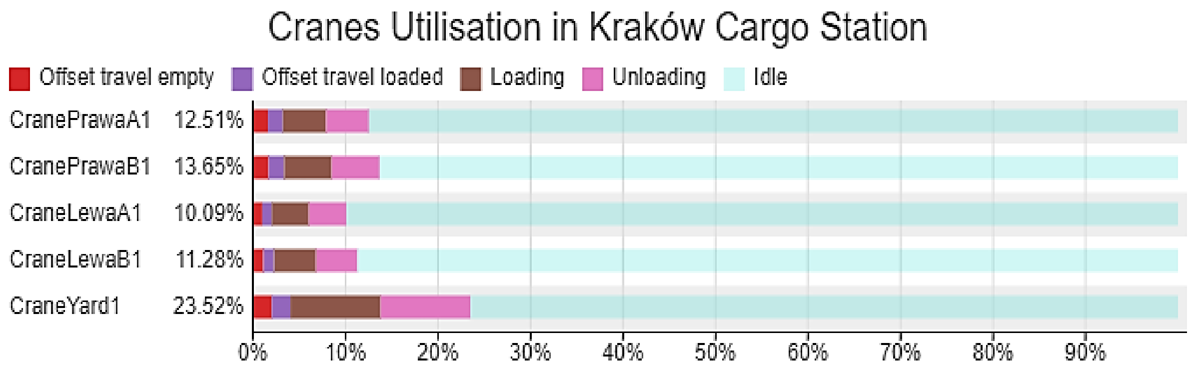

Figure 9. Cranes utilization in Krakow Cargo Station.

Source: Own elaboration.

Figure 9 illustrates the percentage breakdown of operation time for five cranes, considering different operational states. Five categories are highlighted: empty transit time, transit time with cargo, loading time, unloading time and idle time. The most efficiently used crane is CraneYard1, which achieved a 23% utilization rate. In its case, there is a noticeably higher proportion of time dedicated to loading operations compared to the other cranes. The load data for autonomous forklifts is presented in Figure 10.

The charts related to crane and autonomous forklift utilization compare the usage of these components throughout the entire duration of the simulation. As a result, the percentage values appear relatively low, since these elements are utilized only during the operation of the freight station, which occurs during the nighttime period. However, noticeable peaks in activity during container loading and unloading operations indicate potential local infrastructure overloads. Similar analyses were performed for the other cities involved in the simulation. The load on the cranes and AGVs at the Warsaw station, presented in Figure 11, is comparable to the results observed in Krakow. This suggests that the current model assumptions are sufficient to handle the projected traffic. Variations in system load across different locations may result from differing transportation demands at each station.

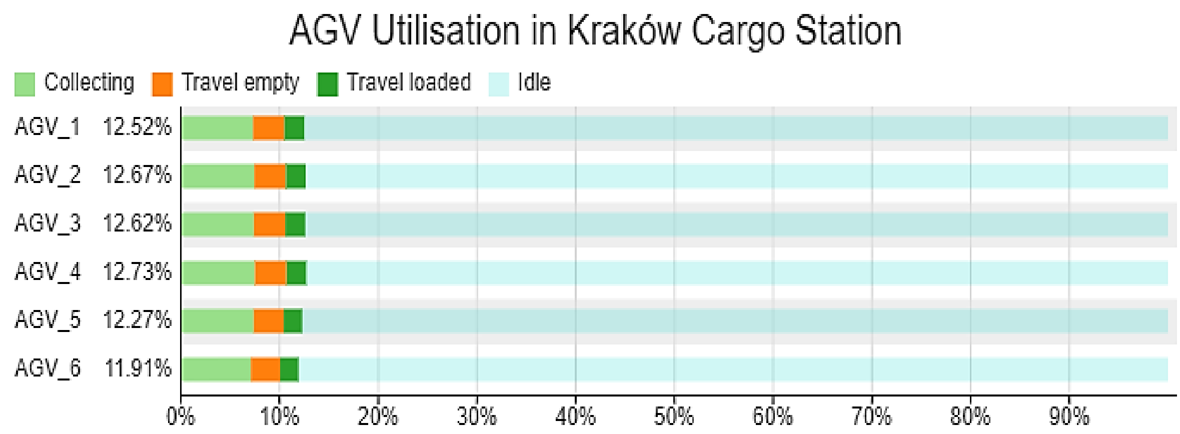

Figure 10. AGV utilization in Krakow cargo station.

Source: Own elaboration.

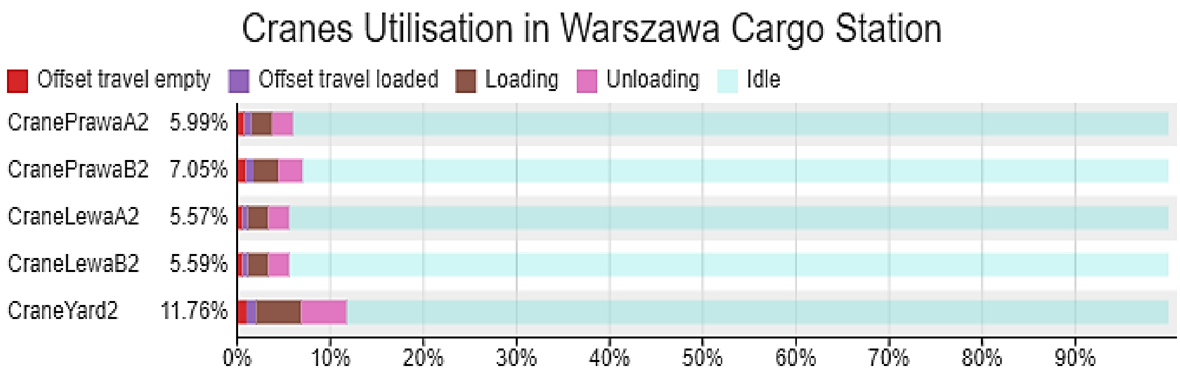

Figure 11. Cranes utilization in Warsaw Cargo Station.

Source: Own elaboration.

Due to changes in traffic operations at 6:00 a.m. and 11:00 p.m., freight capsules departing at these times must wait in line to enter the tube through the airlock. This situation represents a bottleneck in the Hyperloop transportation system, as the air evacuation and re-inflation process for the airlock requires time. Such delays impact overall transport operation times. Figure 12 illustrates the increased number of capsules waiting for access to the tubes during transition periods. This result emphasizes the need to optimize the traffic schedule to minimize waiting times for freight capsules and ensure smooth operations.

The simulation model enabled a detailed analysis of the system's operation, offering valuable insights into its dynamics and performance. However, further research and development are required to improve the accuracy of the results, especially concerning the system's capacity and the potential application of the technology in freight transport.

Future research may focus on refining model parameters, incorporating more detailed real-world constraints and investigating innovative technological solutions. Implementing these measures will support a comprehensive understanding of the system's capabilities, considering both its operational efficiency and adaptability to evolving logistical challenges.

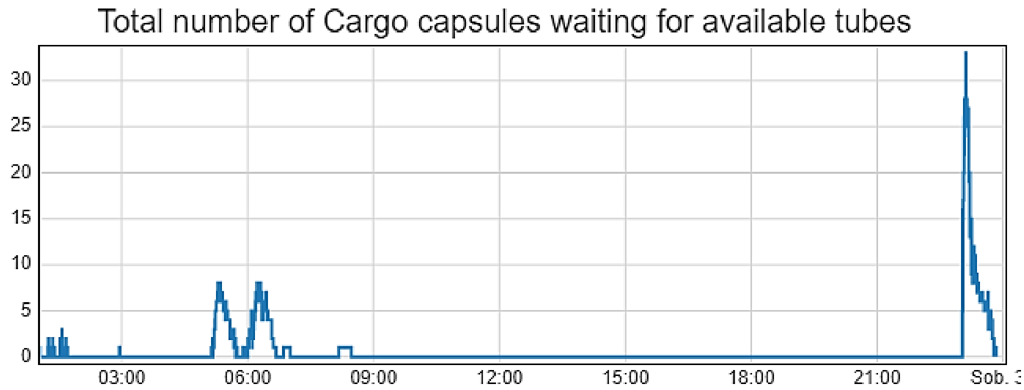

Figure 12. Total number of cargo capsules waiting for available tubes.

Source: Own elaboration.

5. Discussion

The Hyperloop system, with the assumed operational parameters, demonstrates the capability to handle a significant number of passengers and transport containers during the nighttime operations, positioning it as a promising alternative to traditional transportation methods in the context of sustainable development. These results effectively address the research question concerning the system's ability to manage passenger and freight flow both efficiently and sustainably.

The research findings have been contextualized within the existing literature, which demonstrates that traditional transportation methods are less efficient than Hyperloop technology in terms of energy consumption and time. The conclusions drawn from the simulations support these claims, while also emphasizing the potential of Hyperloop to integrate seamlessly with existing logistical infrastructure. The system distinguishes itself through its ability to deliver rapid transport and high throughput, aligning with the trend of environmentally friendly technologies that meet global transportation demands.

One of the unexpected results of the study was the identification of bottlenecks in the system's operation, particularly at 6:00 a.m. and 11:00 p.m., when freight capsules must wait for access to the airlocks. The process of pumping air into and out of the tubes is time-consuming, resulting in delays in transport operations. This limitation underscores the need to optimize airlock operation schedules or to implement more efficient technologies that could reduce downtime and improve overall system performance.

It is important to emphasize that the study was conducted in a simulation environment, which entails certain limitations in fully reflecting real-world operational conditions. The simulations do not consider random variables, such as technical failures or external factors, that could influence the results. Moreover, the assumed operational parameters, such as the frequency of capsule departures, may differ in practice, highlighting another area that warrants further investigation.

The conducted analyses also suggest potential directions for future research, which could include more detailed operational modeling that accounts for random variables and the impact of disruptions on the system's performance. Further studies could also focus on optimizing work schedules, improving airlock operations and integrating Hyperloop with other transportation modes. Such research would provide a deeper understanding of the technology's impact on global logistics networks. The findings demonstrates that Hyperloop has the potential to become a key component of future transportation systems, offering a combination of efficiency, speed and minimal environmental impact.

6. Conclusion

The results of the conducted simulations confirm the potential of Hyperloop technology as an innovative transportation system capable of handling both passengers and cargo. The simulation model enabled the analysis of the system's capacity, the load on logistics infrastructure and the integration of passenger and cargo traffic. The obtained data indicates that, under the assumed operational parameters, the system can accommodate a significant number of passengers and cargo according to the planned schedule.

Passenger transport throughout the day facilitated the movement of 42000 passengers, highlighting the system's high efficiency. Cargo transport, which enabled the delivery of 183 containers, demonstrates the significant potential of utilizing nighttime time slots to optimize cargo flow. The analysis also identified key challenges related to coordinating passenger and cargo traffic to ensure safe travel and minimize potential downtime.

The load on the additional infrastructure used in cargo transport, such as cranes and autonomous AGV vehicles, was balanced, indicating the potential for further intensification of cargo movement. Developing an optimal schedule for the operation of logistics equipment is crucial, taking into account the varying demand between stations to prevent system overload and ensure smooth and efficient operations.

The conclusions drawn from the analysis highlight that the Hyperloop system has the potential to become a key element of future transportation, thanks to its combination of high speeds, operational efficiency and minimal environmental impact. To fully leverage the capabilities of this technology, further research is necessary to refine the traffic schedule, integrate dynamic management systems and conduct detailed analyses of potential failures and maintenance interruptions that could affect the system's operation.

Future actions should focus on improving the precision of operational models and adapting them to real-world conditions in both passenger and cargo transport. Further optimization of logistical infrastructure, along with an analysis of long-term economic and environmental benefits, will support better utilization of the Hyperloop technology's potential as a new transportation standard.

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