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ENHANCING PASSENGER FLOW AT SUBWAY TRANSFER STATIONS THROUGH SIMULATION MODELING

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ABSTRACT

With the increased popularity of the public transportation field, congestion in multi-line subway transfer hubs has become one of the hot issues. This study presents a comprehensive simulation model utilizing AnyLogic software to evaluate the performance of the 59th-Street-Columbus Circle subway transfer station in New York City by addressing challenges of inefficient passenger flow management. Leveraging the NYC turnstile usage data, the simulation focuses on this major three-level transfer hub to analyze passenger flows, identify bottlenecks, and evaluate potential solutions. Extensive simulation experiments reveal critical high-density regions prone to severe congestion, particularly at intersections. With an inverse relationship between crowd density and average passenger speed, higher densities lead to near-stagnant conditions during peak hours. By providing data-driven insights through simulation analyses, this research aims to enhance the commuter experience, reduce delays, ensure efficient behavior at vital transit hubs, and contribute to more-sustainable urban transportation by encouraging public transit usage.

1 INTRODUCTION

Subway transfer stations are critical nodes in urban rail transit systems, serving as connecting points where passengers can change lines or modes of transportation. These stations play a pivotal role in facilitating seamless travel and ensuring the efficient movement of commuters within cities. However, the operation of transfer stations is often delayed by various challenges that can lead to congestion, long waiting times, and overall inefficiency (Shi et al. 2020). One of the primary challenges faced in transfer station behavior is the management of high passenger volumes during peak hours. The convergence of multiple transit lines at these stations can result in overwhelming crowds, straining the station's capacity and leading to bottlenecks (Kim et al. 2017). Insufficient passenger flow management, badly organized subway transfer routes, and complex construction design can further exacerbate these issues, causing overcrowding and potential danger to all passengers (Li and Zhou 2013). Another significant challenge is the coordination of train schedules and dwell times. Misalignment between the arrival and departure times of different transit lines can lead to extended waiting periods for transferring passengers, thereby reducing the overall efficiency of the system (Nie et al. 2021). Additionally, unexpected platform overload and travel delays due to passenger congestion can disrupt the entire network, causing profound effects throughout the transit system.

To address these challenges and evaluate the performance of subway transfer stations, simulation modeling has emerged as a powerful tool. Simulation techniques enable the construction of virtual representations of transfer stations, allowing for the exploration of various scenarios and the evaluation of different strategies before implementation in the real world (Li et al. 2012). By leveraging simulation models, transportation planners and operators can gain valuable insights into the complex dynamics of passenger flow, identify potential bottlenecks, and test the effectiveness of proposed solutions. Meanwhile, it can also help to analyze the impact of layout modifications, operational adjustments, and passenger flow management strategies on transfer station efficiency. This approach enables data-driven decision-making, facilitating the identification of optimal solutions that can minimize congestion, reduce waiting times, and enhance the overall experience for commuters (Zhang et al. 2022). The significance of this research lies in the development of more efficient and sustainable urban transportation transfer systems. By optimizing the passenger flow and travel time of subway transfer stations, cities can encourage a higher capacity of public transit, reduce reliance on private vehicles, and mitigate the negative environmental impact associated with traffic congestion and emission.

2 LITERATURE REVIEW

Numerous research efforts have been addressing the challenges faced in subway transfer station behavior through various approaches, especially in simulation modeling. One study highlighted the potential of dynamically adjusting pedestrian routing and crowd control measures to alleviate congestion and reduce waiting times at transfer stations (Owais et al. 2021). Another study employed a discrete event simulation approach to analyze the effects of platform and concourse layout modifications on passenger movements and overall station performance (Xu et al. 2014, Yang et al. 2017). In addition to layout optimization, researchers have also explored the role of operational strategies in enhancing transfer station efficiency. For example, a simulation framework was utilized to investigate the benefits of real-time train rescheduling and dynamic platform assignment adjustments in response to disruptions or overcrowding situations at transfer hubs. The findings demonstrated the potential for significant improvements in passenger throughput and reduced transfer times by implementing such measures (Yap et al. 2019).

Simulation modeling techniques have been widely adopted across various transportation domains to study complex systems and evaluate potential solutions, encompassing diverse methodologies and applications. Discrete event simulation (DES) and agent-based modeling (ABM) are among the most commonly employed simulation approaches in the context of subway transfer station optimization (Marsha et al. 2021). DES models simulate the movement of discrete entities (e.g., passengers) through a system over time, effectively capturing their interactions at a microscopic level and enabling the study of the overall system dynamics that emerge (Zhang et al. 2014). On the other hand, ABM is focused on modeling the individual behavior and decision-making processes of autonomous agents within the system, allowing for the exploration of emergent patterns and phenomena arising from the interactions between agents and their environment.

Other simulation techniques have also found valuable applications in the analysis and design of transportation systems. Microsimulation models provide an extremely detailed representation by simulating the movements and interactions of individual entities such as vehicles or pedestrians within the system. While computationally intensive, this high-fidelity approach can capture intricate dynamics that may be overlooked in more aggregate models (Merz 1991). Contrastingly, mesoscopic simulation aims to strike a balance between computational efficiency and the level of detail modeled, representing entities at an intermediate level of aggregation between microscopic and macroscopic scales. This approach can be advantageous when studying large-scale systems where a fully disaggregated representation is infeasible or unnecessary.

While the studies conducted to date have contributed valuable insights into optimizing subway transfer station behavior, several significant gaps remain in the existing literature. Many research efforts have focused narrowly on specific aspects of transfer station design or behavior, such as layout configuration, passenger flow management strategies, or operational policies, without comprehensively considering the complex interactions and combined impact of these factors on overall system efficiency. Furthermore, a substantial portion of prior work has relied heavily on simplified assumptions, limited real-world data, or isolated case studies, potentially failing to adequately capture the nuances, variabilities, and multi-faceted nature of large complex transfer station environments.

Addressing these gaps, this research study aims to develop a comprehensive, agent-based simulation model that captures the dynamic of passenger flow and movement in a subway transfer station. The research could give inspiration for future passenger throughput management such as station layout and transfer route design, operational decision policies, crowd management procedures, and stochastic demand patterns. By leveraging advanced simulation techniques, extensive real-world data sets, and empirically grounded behavioral models, this research endeavors to provide a more realistic and representative virtual environment for studying transfer station performance under diverse scenarios.

3 METHODOLOGY

3.1 Anylogic Software

Anylogic is a multifaceted simulation software that supports system dynamics, discrete events, and agent-based modeling. It is well-known for its flexibility and capacity to model complex systems in various fields, including transportation, healthcare, manufacturing, and logistics. For this study, Anylogic's comprehensive toolkit for transportation and pedestrian flow simulation offers a robust platform to accurately model the intricacies of passenger movements and interactions within a subway system. The software's ability to integrate different simulation methodologies and its extensive library of pre-built models and components make it an ideal choice for modeling the dynamic environment of a transfer subway system. Additionally, Anylogic's pedestrian generator library is specifically designed to simulate the behavior and movements of individuals in crowded spaces, making it particularly relevant for this study of passenger flow in subway systems.

3.2 Simulation Model

Within this model, the authors simulate the multifaceted process by which passengers transfer between lines as they travel towards their destinations. This includes the detailed modeling of train arrivals, passenger flows, as well as flow exchange between layers, which are fundamental components of the system's operation, influencing passenger flow and the overall efficiency of the subway network. At its core, a discrete event simulation framework is deployed to model the movement of passengers through the transfer station over time. Discrete event logic models and simulates the operational process, including train schedules, platform assignments, and crowd control measures. Besides the discrete event simulation framework, an agent-based modeling element is also incorporated to capture the decision-making process and dynamic patterns that arise from the interaction between individuals. Each passenger will be represented as an autonomous agent with different arrival time, subway station entrance selections, and route planning between platforms. This agent-based element will help to explore the microscopic behavior scaled up to macroscopic behavior, such as crowd formation, bottlenecks, and congestion patterns. By seamlessly combining these simulation techniques, the proposed model will offer a realistic and multi-scale representation of transfer station behavior. It will enable the analysis of diverse scenarios, ranging from routine behavior to disruptions, crowding, and emergency situations. The model will be calibrated and validated using extensive real-world data, including passenger flow data from NYC turnstile counts.

By capturing these key dynamics, the model offers a powerful tool for understanding and improving the efficiency and user experience of subway systems with line transfers. It enables transportation planners and engineers to test various operational strategies and station designs in a virtual environment, thereby identifying solutions that can enhance the flow of passengers, reduce congestion at critical points, and ultimately improve the overall performance of the subway network. To conduct the simulation, the following assumptions are adopted:

1. Train Arrival Times: Trains arrive at each station according to a Poisson process with rate λ_t , which simplifies the variability of arrival times during peak and off-peak hours.

2. Passenger Arrival Rates: Passengers arrive at stations following a separate Poisson process with rate λ_P , differentiated for peak and off-peak hours.
3. Walking Speeds: All passengers are assumed to have a uniform walking speed v, simplifying the model by not accounting for variability among individuals.
4. Transfer Decisions: Passengers choose the shortest path to their destination without considering real-time conditions such as congestion or delays.

In the simulation, Queueing Theory is used for the passenger source generator. Queue models allow us to simulate various scenarios with a high degree of realism by capturing the essence of how passengers arrive, wait, and are serviced boarding or alighting trains. These models are based on probabilistic laws that account for the randomness of events such as train arrivals and passenger entry into the station. By leveraging these models, the impact of different factors – such as train frequency, platform layout, and passenger arrival rates – on overall system efficiency and passenger satisfaction is evaluated (Wang et al. 2021):

- Train Dynamics: The time between train arrivals T_a at a given station for a specific line follows an exponential distribution due to the Poisson process assumption:
$$T_a \sim Exp(\lambda_t) \tag{1}$$
- Passengers Arrival Dynamics: The number of passengers N_P arriving at a station in a given time interval follows a Poisson distribution:
$$N_P(t) \sim Poisson(\lambda_P * t) \tag{2}$$
- Passenger Flow and Congestion: The model of passenger flow through the station, especially at transfer points, uses an M/M/1 queueing system for simplicity, where the arrival rate λ_P and service rate μ (related to train capacity and frequency) are key parameters. The average number of passengers in the system N_s and the average time a passenger spends in the system T_s are given by:
$$N_s = \frac{\lambda_P}{\mu - \lambda_P} \tag{3}$$
$$T_s = \frac{1}{\mu - \lambda_P} \tag{4}$$
- Train Capacity Constraints: The probability P_k that k passengers board a train is modeled assuming a binomial distribution, reflecting the constraint of train capacity:
$$P_k = \binom{C}{k} P_k (1 - P_k)^{C-k} \tag{5}$$

Besides, passengers normally move between B1, B2 and middle layers. This movement is driven by the need to transfer between lines or access different station exits. This paper identifies $r_{B1\to Middle}$, $r_{Middle\to B2}$, as well as $r_{Middle\to B1}$, $r_{B2\to Middle}$ as the rate of transition between layers. The Passenger Flow Dynamics can be expressed as:

- For B1 layer:
$$\Delta P_{B1} = -r_{B1\to \text{Middle}} \cdot P_{B1} \cdot \Delta t + r_{\text{Middle} \to B1} \cdot P_{\text{Middle}} \cdot \Delta t \tag{6}$$
- For Middle layer:
$$\Delta P_{Middle1} = \left(r_{B1\to \text{Middle}} \cdot P_{B1} + r_{B2\to \text{Middle}} \cdot P_{B2}\right) \cdot \Delta t \tag{7}$$
$$\Delta P_{Middle2} = \left(r_{Middle\to \text{B1}} \cdot P_{Middle} + r_{Middle\to \text{B2}} \cdot P_{Middle}\right) \cdot \Delta t \tag{8}$$
$$\Delta P_{\text{Middle}} = \Delta P_{Middle1} - \Delta P_{Middle2} \tag{9}$$
- For B2 layer:
$$\Delta P_{B2} = -r_{B2\to \text{Middle}} \cdot P_{B2} \cdot \Delta t + r_{\text{Middle} \to B2} \cdot P_{\text{Middle}} \cdot \Delta t \tag{10}$$

3.3 Data Collection and Preparation

When developing the simulation model focused on a subway station with line transfers, the foundation of realistic and accurate modeling lies in the robustness and relevance of the data collected. For this purpose, the primary dataset was the 2022 turnstile usage data, which provides comprehensive information on passenger flows within the New York City's subway system. This dataset, publicly available and widely regarded for its granularity and accuracy, records the number of entries and exits at each turnstile within the subway system, offering a detailed snapshot of passenger movements across different times and stations. This paper chooses the 59th-Street Columbus Circle station in New York City as the base model. Selecting this station as the simulation focus, the study leverages the essence of this major transfer hub within the New York City Subway system, distinguished by its high passenger volume, service by multiple lines, and a complex three-layered layout (B1, Middle, B2) as shown in Figure 1. This structure makes it a prime candidate for a detailed analysis of passenger movements, including transfers between different levels and the impact of station design on flow and congestion. The availability of comprehensive operational data supports the development of an accurate simulation model. Insights from this pivotal station are not only directly applicable to optimizing its operation and enhancing the commuter experience but also offer valuable strategies that can be scaled to improve the broader subway network, addressing challenges inherent to multi-layered urban transit systems.

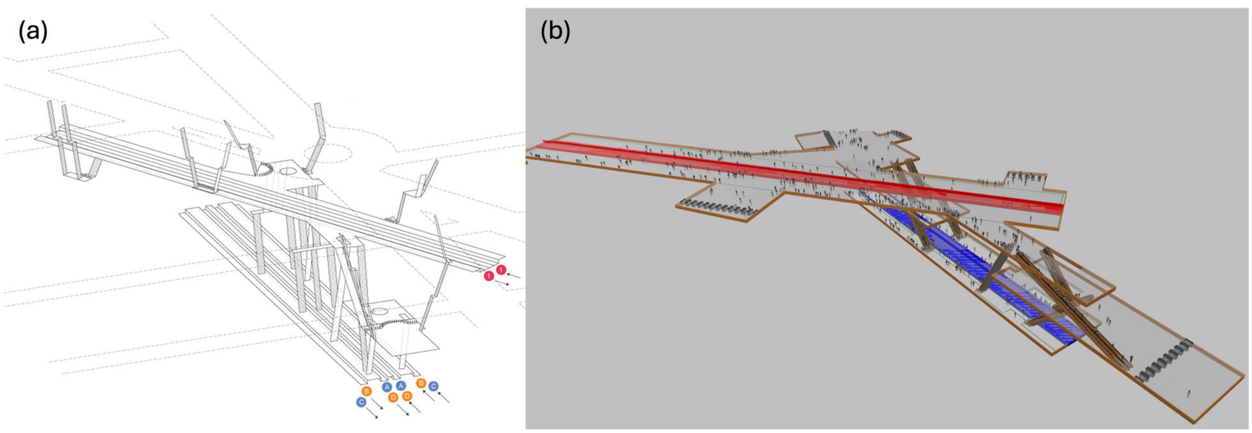

Figure 1: 59th-Street Columbus Circle: (a) construction design (3D Models); (b) Anylogic simulation environment set up.

The raw turnstile usage data, while extensive, required significant preprocessing to align it with the needs of the simulation model. The following steps were taken to clean the data:

- Normalization of arrival rates: Given the variability in passenger arrivals across different days and hours, this paper normalized the data to fit the simulation timeframe. This involved calculating average hourly arrival rates for a typical weekday, allowing us to model both peak and off-peak scenarios with a high degree of accuracy.
- Adjustment of train capacities: To reflect real-world constraints and operational practices, the study adjusted the train capacities in the model based on the observed maximum and average passenger counts during peak hours. This adjustment ensures that the simulation realistically captures the limits of the system's capacity to accommodate passenger flow.
- Remove outliers and missing values: This step involved removing anomalies and outliers from the data, such as days with atypical usage patterns (due to holidays or special events) and turnstiles with malfunctioning counters, ensuring the cleanliness of the data was paramount to maintaining the integrity of the simulation results.

- Timeframe segmentation: To accurately model different parts of the day, the data have been segmented into time blocks corresponding to periods. The Poisson distribution is calibrated from the turnstile schedule data due to the absence of inherent stochastic properties in the deterministic schedule. This calibration allows for the incorporation of randomness and variability in passenger arrivals, which the schedule data alone cannot adequately represent.

The turnstile data indicate a time-of-day pattern where passenger traffic is lowest in the early morning (00:00-04:00) and increases sharply for the morning rush (08:00-12:00), with the station seeing the highest exit numbers. Midday hours (12:00-16:00) show the peak in both entries and exits, indicating the busiest period. Late afternoon into evening (16:00-20:00) remains busy, especially for entries. Late-night hours (20:00-00:00) experience a moderate decrease in traffic. These patterns reflect typical rush and off-peak hours of urban subway use.

Table 1: Passenger flow in time-of-a-day.

Hour	Statistic	Sum	Mean	Std Dev	Min	Max
20:00-0:00	ENTRANCE	4,625	3,263	1,680	784	88,110
	EXIT	3,899	3,002	2,020	517	81,057
0:00-4:00	ENTRANCE	700	486	252	117	13,611
	EXIT	1,082	574	298	238	16,059
4:00-8:00	ENTRANCE	1,302	897	415	330	25,126
	EXIT	6,768	4,271	874	2,190	119,587
8:00-12:00	ENTRANCE	4,489	3,313	1,730	899	89,460
	EXIT	17,333	11,526	4,364	4,921	311,198
12:00-16:00	ENTRANCE	9,760	6,715	3,535	2,001	188,012
	EXIT	18,963	9,441	6,300	2,120	264,344
16:00-20:00	ENTRANCE	13,715	9,353	3,831	3,354	261,873
	EXIT	10,933	8,415	5,101	1,464	235,615

3.4 Simulation Flow Setup

The simulation flow setup involves multiple interconnected steps (Figure 2). Initially, the inputs include a passenger flow generator, transfer station design, and subway time schedule data. These feed into setting up the geometry and underlying algorithms, incorporating elements like passenger flows from different lines, escalator movements, entrance turnstiles, and train schedules across multiple lines. The core passenger flow interconnection happens through distinct layers – B1, middle, and B2 – representing different sections or floors of the transfer station. Finally, the simulation outputs include data recording and visualization via heat maps, providing insights into passenger density and movement patterns across the various interconnected areas of the station complex. This modular approach aims to accurately model the intricate passenger flows, transfers, and potential bottlenecks within the multi-level multi-line subway station environment.

4 EXPERIMENT RESULTS AND ANALYSIS

The simulation experiments yielded extensive data and insights into the passenger flow dynamics at the 59th-Street Columbus Circle subway transfer station. One of the key findings was the identification of critical bottlenecks and high-density regions within the station complex. The regional density maps generated from the simulation models revealed several hotspots where passenger congestion tended to occur, particularly at intersections of major pedestrian pathways and near entrances and exits. These areas were marked by deep red zones, indicating dangerously high crowd densities that could potentially impede efficient passenger movement and pose safety risks. Notably, the congestion levels appeared to worsen during simulated peak hours, exacerbating the bottleneck effects. Further analysis of the time distribution data highlighted prolonged dwell times for passengers attempting to enter or exit the station through these bottleneck areas, with some individuals experiencing delays of over ten minutes to complete their transfers.

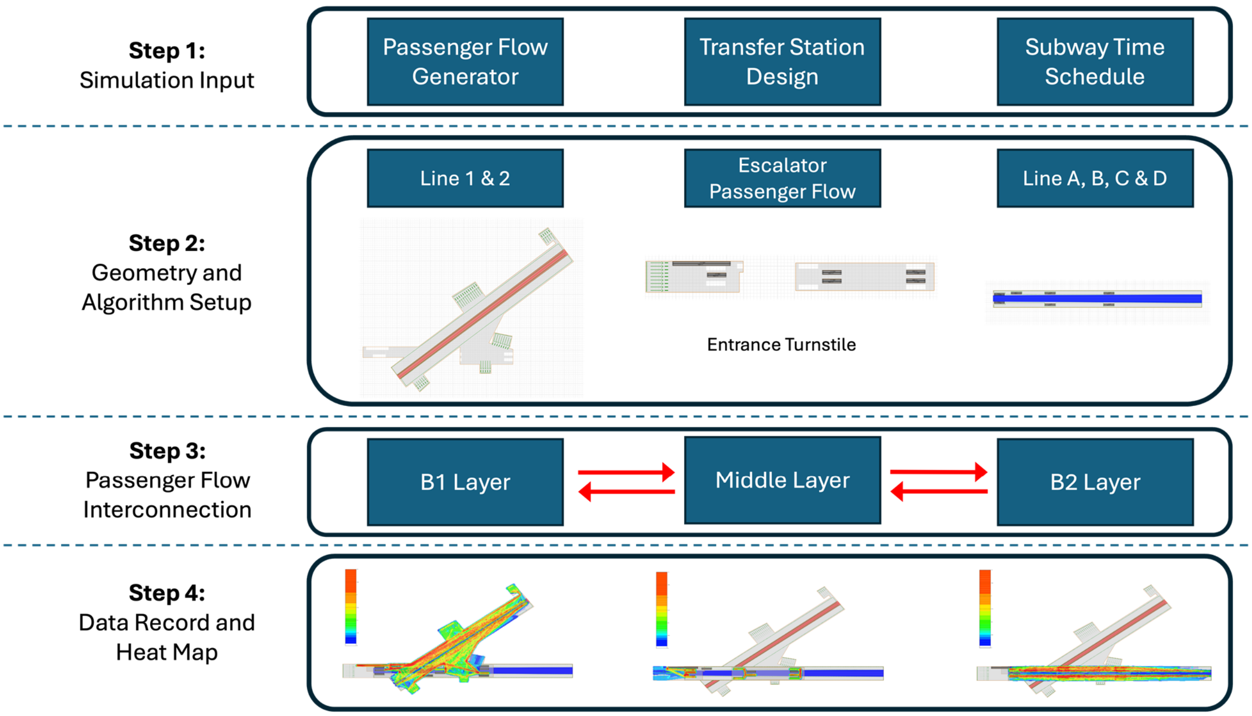

Figure 2: Simulation modeling pipeline.

According to Figure 3, the overall heatmap in the top left corner suggests that the majority of passenger flow is concentrated along the main thoroughfare of the station, with particularly high densities at platform access points, turnstile areas, and especially at junctions where passengers might converge or diverge from different directions. The B1 layer heatmap in the top right shows a similar pattern but with reduced density, indicating this level might be less traveled or has a more efficient flow. The middle layer in the bottom left shows less intensity in density, suggesting it could be a transition area or a less busy platform. The B2 layer heatmap in the bottom right, conversely, displays a high-density area on the platforms themselves, which could correspond to either a busy line or a bottleneck in passenger movement. These maps are instrumental for understanding the flow and can inform station management and design to improve traffic, enhance safety, and increase efficiency by, for example, expanding capacity in high-density areas or optimizing the flow in transition zones.

Another crucial aspect examined by simulation was the average passenger flow speed within the station. The results demonstrated a clear inverse relationship between crowd density and average speed, with higher densities leading to slower overall passenger movements. During off-peak periods, when the station was less crowded, the average speed hovered around the expected range of 0.5-0.7 meters per second. However, as passenger volumes increased, the average speed progressively decreased, dropping to alarmingly low levels of 0.2-0.3 meters per second during the simulated peak hours. This drastic reduction in speed not only caused significant delays for individual passengers, but also had ripple effects on the overall efficiency of the transfer process. Furthermore, the simulation revealed a bunch of low-motion flow in specific high-density areas, where passengers were essentially trapped in a crowd lock, unable to make meaningful progress towards their destinations. Figure 4 illustrates the average speed of pedestrians over the simulation time. The initial high speed (around 9 km/h) rapidly decreases and fluctuates around 3 km/h for the majority of the simulation duration. This pattern suggests that pedestrians encounter congestion or obstructions that cause their speed to decrease and vary over time. Such variations in pedestrian speed can contribute to the formation of bottlenecks and congestion within the station. The queue length at the B1MiddleOut location, as shown in Figure 5, exhibits periodic spikes, indicating recurring periods of congestion or bottlenecks at this particular point within the station. In Figure 5(c), the queue length rises sharply to around 0.8 persons and then quickly dissipates, suggesting short-lived congestion events. However, in Figure 5(d), the queue length shows more pronounced spikes, with some peaks reaching up to 2.8 persons, potentially representing more severe congestion episodes at the B1MiddleOut location.

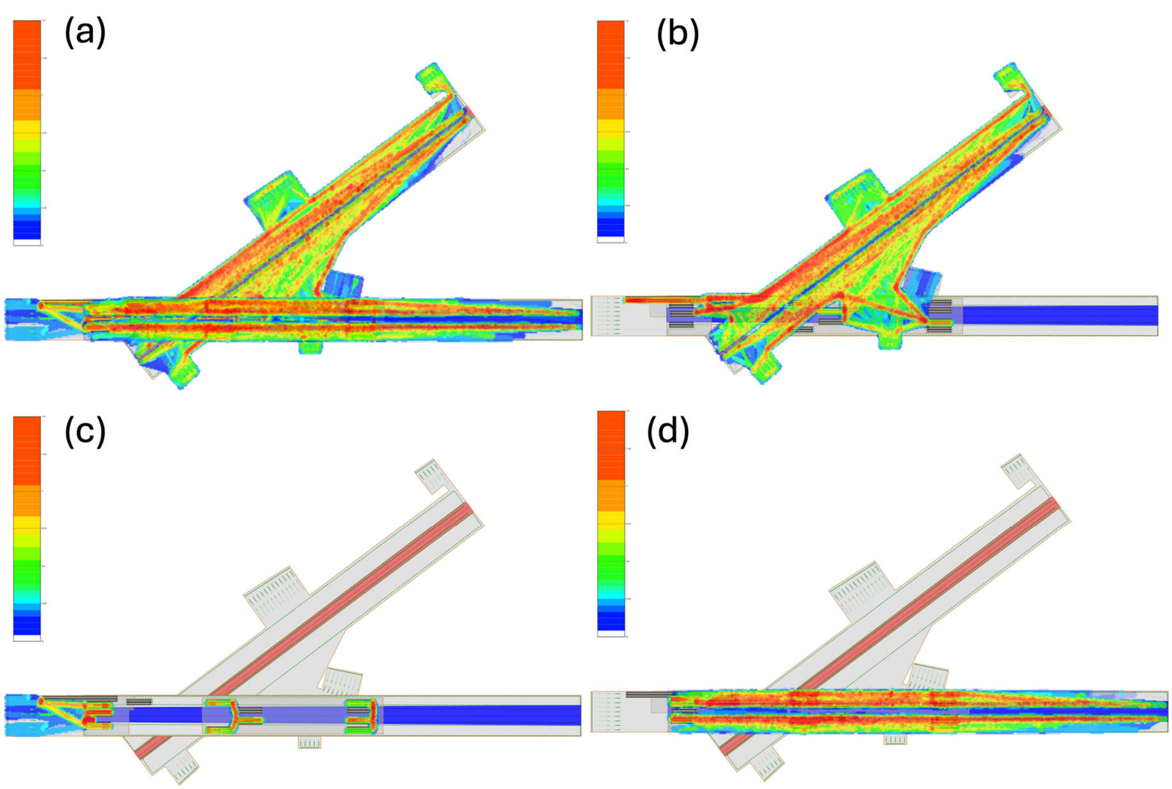

Figure 3: Passenger flow heatmap: (a) overall; (b) B1 Layer; (c) Middle Layer; (d) B2 Layer.

Based on the comprehensive simulation data, it became evident that the current station design and operational strategies were inadequate to handle the projected passenger volumes, particularly during peak periods. The analysis highlighted the need for targeted interventions and design modifications to alleviate the identified bottlenecks and improve overall transfer efficiency. Potential solutions could involve reconfiguring pedestrian pathways, strategic placement of barriers or guidance systems to better organize passenger flows, and increasing the capacity of critical chokepoints through additional entrances and exits or wider corridors. Additionally, the simulation underscored the importance of implementing dynamic crowd management strategies, such as adaptive signage, real-time monitoring, and proactive personnel deployment to manage congestion during peak hours. By scenario exploration and parameter tuning, the optimal scenario with the least system total waiting time was identified, in which the two parameters passenger arriving rate λ_p and rate of transition r are significantly lower than the baseline scenario. By leveraging these insights, transit authorities can enhance the commuter experience, reduce delays, and ensure the safe and efficient operation of this vital transportation hub. According to Figure 6, all three layers are suffering travel delays, at least three times during the overall simulation. Among them, the B2 Layer has a longer tail on delay distribution, indicating that it has a greater probability of longer delay.

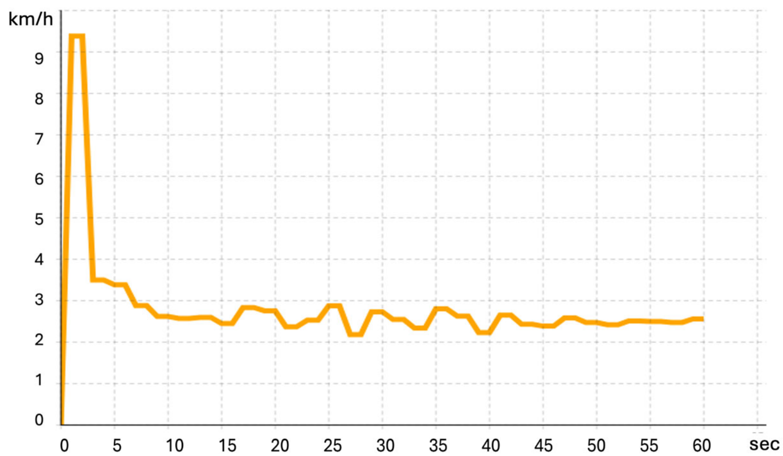

Figure 4: Average speed of pedestrians.

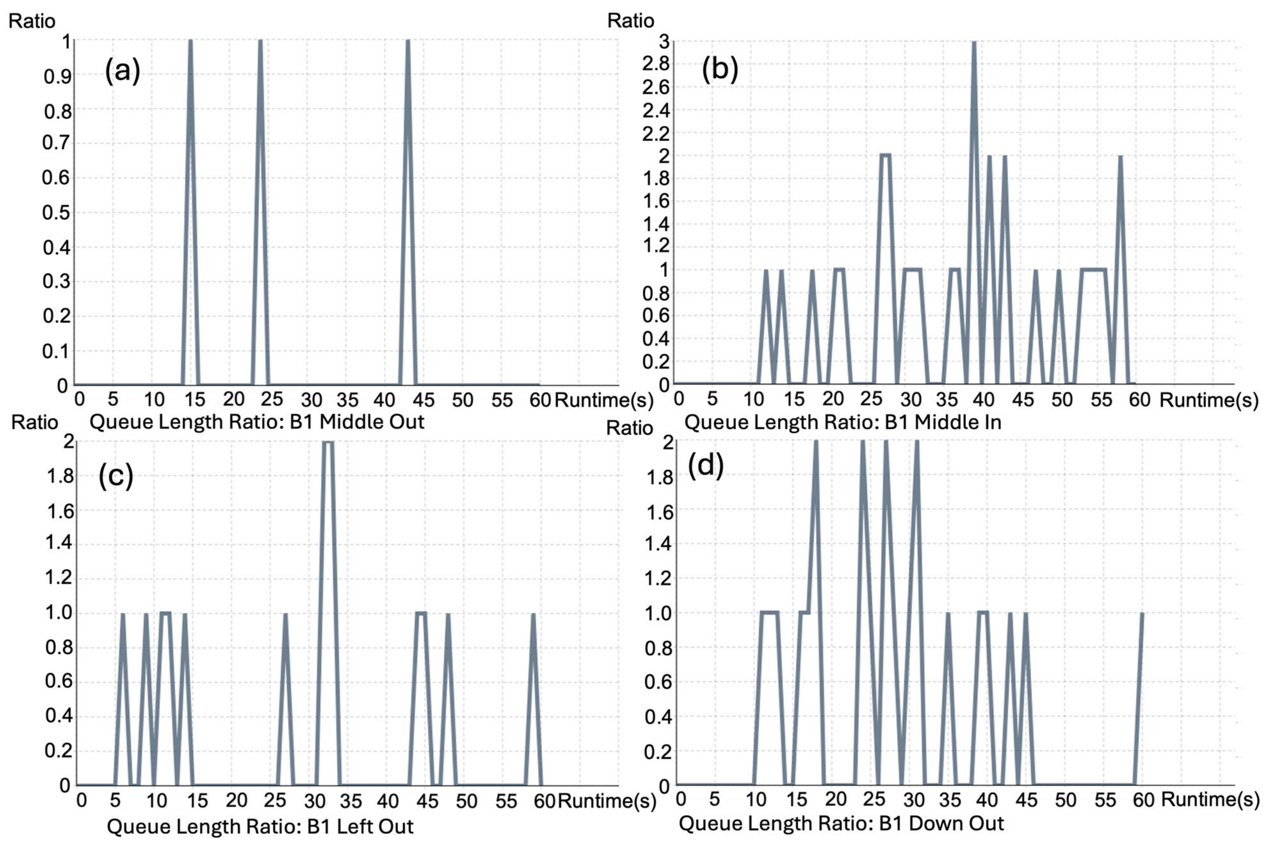

Figure 5: Queueing length over simulation time: (a) B1 Middle Out; (b) B1 Middle in; (c) B1 Left Out; (d) B1 Down Out

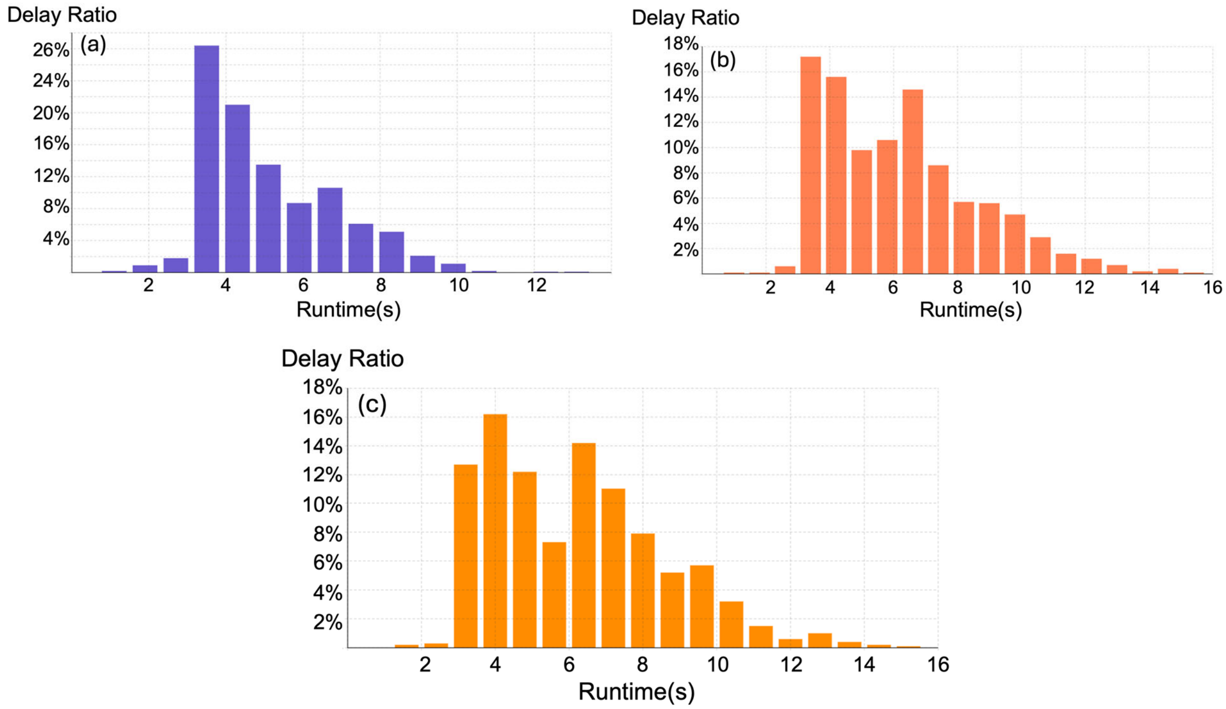

Figure 6: Average delay on Layers (a) B1; (b) Middle; (c) B2.

These findings highlight the importance of identifying and addressing potential bottlenecks or congestion points within the subway station. The periodic spikes in queue lengths at specific locations, such as B1MiddleOut and B1DownOut, warrant further analysis and the implementation of mitigation strategies to improve passenger flow and reduce congestion. Additionally, the varying arrival patterns and pedestrian speeds observed underscore the need for a comprehensive approach to optimizing the station's design and behavior to accommodate diverse pedestrian behavior and dynamics.

5 CONCLUSION

This comprehensive simulation study employed the AnyLogic software to comprehensively analyze and evaluate the passenger flow dynamics and transfer efficiency at the critically important 59th-Street Columbus Circle subway transfer station in New York City. By constructing detailed computational models and running various simulated scenarios, the research was able to gain unprecedented insights into key performance metrics such as local crowd densities, average pedestrian speeds, and time distributions for entering and exiting the station premises. These quantitative measures provided an objective lens through which to assess the station's operational capabilities and identify potential shortcomings or areas requiring improvement.

The initial simulation runs yielded worrying results that brought to light several significant issues because of the station's current infrastructure and design. Alarmingly high regional densities were detected at multiple convergence points and intersections where passenger flows from various directions converged. These hotspots of overcrowding not only prevented the smooth movement of individuals, but also exposed potential safety hazards due to the increased risk of crowd-related incidents. Furthermore, the time distribution data revealed extended delays experienced by passengers attempting to enter or exit the station through these congested bottleneck areas, with some commuters enduring frustrating wait times exceeding ten minutes to complete their transfers.

Compounding the challenges posed by localized crowding, the simulation also uncovered a clear inverse relationship between passenger volume and average flow speed throughout the station complex. As the simulated peak hours progressed and the station became increasingly populated, the overall average speed of pedestrian movement declined precipitously. By the end of the simulation period, these speeds had decreased to sub-optimal levels, indicative of severely unsmooth mobility and stagnant conditions in certain high-density zones. This phenomenon not only exacerbated delays for individual commuters. but also profoundly impacted the overall transfer efficiency of the entire station, thereby undermining its core functional purpose.

The simulation results proposed new directions on the current station's ability to adequately serve the needs of the city's rapidly growing population and the ever-increasing demands placed on its public transportation infrastructure. To be specific, rather than representing an intractable problem, these findings present a valuable opportunity for transit authorities to leverage data-driven insights and implement targeted interventions to alleviate congestion and improve transfer performance. Potential solutions could involve reconfiguring pedestrian pathways, optimizing the placement of vertical transportation facilities such as escalators and staircases, or implementing dynamic crowd control measures during peak periods. By embracing simulation-based analyses and iterative design optimization, urban planners and transportation officials can enhance the commuter experience, increase operational efficiency, and ensure that vital transit hubs like 59th-Street Columbus Circle remain capable of serving the public transit needs of densely populated urban centers.

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