

# Evaluating Operational and Structural Optimization Strategies for Metro Interchange Stations Using Passenger Flow Simulation: A Case Study of Liyuan South Road Station

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## Abstract

While operational and structural optimizations for metro stations are well-studied individually, their synergistic effects and resilience under extreme conditions remain poorly understood. This paper establishes a systematic „simulation-optimization-evaluation“ framework to quantitatively assess and compare the robustness of different intervention strategies. Taking Liyuan South Road Station of the Ningbo Metro as a case study, we evaluate three scenarios: 1. operational adjustments, 2. structural modifications, and 3. an integrated approach. While the integrated scenario yields the most significant density reduction (9.39% on average, 2.31% in maximum density) under forecasted peak flows, its primary advantage lies in its resilience. Stress tests reveal that the integrated scenario maintains safe operational levels even when passenger flow reaches 1.7 times the forecast, whereas the original and single-strategy scenarios exhibit severe congestion at flow multipliers of 1.3 to 1.4. This study demonstrates that the proposed framework is a valuable tool for decision-makers, enabling a holistic assessment that balances efficiency, safety, and resilience against future demand uncertainty. The findings confirm that integrated strategies, despite marginal increases in transfer times, provide superior safety margins and are essential for the long-term sustainability of high-traffic interchange hubs.

## Keywords

metro interchange, passenger flow optimization, crowding risk, simulation model, MassMotion

## 1 Introduction

With the rapid and networked expansion of urban rail transit systems, metro interchange stations—serving as critical nodes where multiple lines intersect—are increasingly facing significant challenges in terms of passenger flow organization efficiency and safety risk management. In recent international conferences such as ITSSC 2023 (Huang et al., 2024), ICTTS 2024 (Geng et al., 2024), and DSIT 2024 (Begisbayev et al., 2024), the topics of intelligent management, operational efficiency, and safety control have emerged as focal points of scholarly and engineering attention. By the end of 2024, the total operational mileage of urban rail transit in China had reached 12,160.77 km, with an average passenger intensity of 0.61 million trips per km per day—an increase of 0.06 million trips/km-day from the previous year, representing a 10.25% growth (China Association of Metros, 2025). These data highlight the urgency of addressing problems such as congestion, disorganized passenger flow, and

heightened safety risks caused by high-density crowding. Effective solutions demand dynamic simulation approaches combined with multi-dimensional, collaborative optimization strategies.

Several incidents have underscored the severity of such risks. For instance, in 2014, an unpleasant odor suddenly spread in a Line 5 carriage of the Guangzhou Metro, triggering panic and a subsequent stampede that injured 13 individuals (People's Daily Online, 2014). In 2015, a fainting passenger at Shenzhen's Huangbeiling Station led to a crowd stampede, resulting in 12 injuries (Phoenix News, 2015). More tragically, during the 2022 Itaewon Festival in Seoul, excessive crowding near a metro exit and adjacent passages led to a fatal crush that caused 159 deaths and 196 injuries (Wikipedia, online). These cases collectively reveal how localized high-density passenger flow, when combined with unanticipated disturbances, can rapidly evolve into systemic safety hazards.

In response to these challenges, substantial academic progress has been made both domestically and internationally in the optimization of passenger flow and safety management at metro interchange stations. Regarding passenger behavior simulation, Daamen and Hoogendoorn (2003) investigated the influence of pedestrian density on movement behavior at bottlenecks through empirical walking experiments, while Kim and Kim (2023) employed agent-based modeling to analyze route choice behavior at Seoul's Gangnam Station. In the realm of evacuation efficiency and risk control, studies (Cheng and Yang, 2012; Peng et al., 2024; Zhong et al., 2022; Zou et al., 2021) have utilized multi-agent simulation models to explore the impacts of station layout and management policies on evacuation performance. Yang et al. (2022) integrated a social force model with a least-cost path model to examine passenger flow strategies under epidemic conditions, whereas Yang et al. (2025) applied machine learning methods to predict evacuation times and proposed bottleneck mitigation strategies. Sun et al. (2024) further contributed by quantifying safety risk thresholds specific to interchange station environments.

From the perspective of facility layout and flow optimization, Xu et al. (2020) proposed intervention scenarios to alleviate bottleneck-induced congestion, while Dai et al. (2024) combined spatial syntax, metacellular automata, and environmental behavior theory to optimize concourse layouts, achieving notable improvements in accessibility and efficiency. He and Dong (2019) evaluated passenger flow reorganization in complex interchange stations through simulation-based analysis.

Furthermore, in terms of real-world engineering applications, simulation tools have been widely adopted to inform practical planning decisions. Li (2019) employed Legion software to simulate a dual-line transfer scenario; Yang and Shen (2019) assessed the viability of interface reservation strategies in station retrofitting; and Meng et al. (2025) used AnyLogic to optimize security checkpoint resource allocation in railway passenger terminals.

Although numerous studies have explored passenger flow management in metro interchange stations, several critical gaps remain. Much of the existing literature focuses on static facility layout optimization or isolated operational strategies, without fully addressing the synergistic effects that can be achieved through the integration of multiple interventions. In particular, dynamic interactions among passengers—such as trajectory variation, density fluctuation, and speed changes—are often oversimplified, limiting the effectiveness of proposed solutions. Therefore, there is a pressing need

for a more holistic and dynamic approach that can simultaneously address flow efficiency and safety risk mitigation through coordinated operational and structural optimization.

To fill this gap, this study proposes a refined approach to reveal the dynamic characteristics of passenger flows in complex interchange environments and to elucidate the mechanisms of risk control. This includes strategies for reducing congestion and improving safety through optimization of facility layouts, operational scheduling, and structural modifications. Based on this foundation, three optimization scenarios are formulated:

1. operational adjustments only;
2. structural modifications only;
3. a comprehensive strategy that integrates both.

A multi-indicator evaluation system is also developed to assess the performance of each scenario, including under conditions of extreme passenger flow stress, to ensure robustness and adaptability.

Taking Liyuan South Road Station of the Ningbo Metro as a case study, the research focuses on typical long-term morning peak congestion and develops an integrated "simulation–optimization–evaluation" framework. This methodology leverages high-precision 3D simulation technology and data-driven analysis to assess the effectiveness and resilience of each optimization scenario. The goal is to provide a systematic, evidence-based foundation for improving station performance in terms of both efficiency and safety.

While many studies have explored passenger flow optimization, they often focus on isolated strategies or lack a systematic evaluation of their resilience against unexpected passenger surges. To address this gap, this paper makes the following contributions:

4. It formalizes an integrated "simulation-optimization-evaluation" framework not just for developing solutions, but for systematically comparing their performance and robustness under a range of conditions.
5. It introduces a passenger flow stress-testing methodology to quantify the failure points of different optimization philosophies (operational, structural, vs. integrated).
6. Through a detailed case study, it provides empirical evidence that integrated strategies, while seemingly incremental, offer non-linear improvements in system resilience, a critical factor for long-term planning. This approach moves beyond static optimization to provide a more dynamic and risk-aware decision-making tool for metro station planning and management.

The proposed methodology is validated using real-world field data and visual modeling techniques. The results confirm the accuracy and practicality of the simulation model, and demonstrate its ability to identify bottlenecks, assess the impact of optimization measures, and support decision-making for urban rail transit systems. Ultimately, the findings offer valuable guidance for improving the operational efficiency, safety management, and emergency responsiveness of metro interchange stations, and hold strong potential for broader engineering applications.

## 2 Principles of dynamic optimization of scenarios

### 2.1 Simulation tool selection and validation

This study employs MassMotion, an ISO9001-TickIT certified 3D crowd simulation software developed by Oasys (online). Its modeling framework has undergone validation in accordance with international standards (International Maritime Organization (IMO), 2016; Ronchi et al, 2013), and its simulation accuracy has been verified across multiple real-world application scenarios (Mashhadawi, 2016; Morrow, 2010; Rivers et al, 2014; ).

The core algorithm of MassMotion is based on Helbing's social force model (Helbing and Molnar, 1995; Helbing et al., 2000), in which each pedestrian agent is treated as an autonomous unit influenced by three types of forces: a purpose-driven force guiding the pedestrian toward their destination, an individual repulsive force accounting for inter-agent avoidance, and an environmental avoidance force enabling interaction with spatial obstacles. This modeling framework allows MassMotion to capture both micro-level pedestrian behaviors—such as avoidance, queuing, and dynamic path switching—and macro-level crowd phenomena, including density gradients and congestion propagation.

MassMotion supports high-fidelity 3D modeling of interchange station layouts and incorporates a built-in path planning mechanism. This enables pedestrian agents to dynamically select among multiple routing options and locally re-plan paths in response to congestion or environmental changes, making it particularly suitable for simulating complex, real-world transit environments.

While this study focuses on scenario optimization rather than simulation tool benchmarking, it is important to acknowledge that MassMotion has been independently validated and compared with other pedestrian simulation platforms in previous research. For instance, Anvari et al. (2017) conducted a benchmark study comparing MassMotion with STEPS, Pathfinder, FDS+Evac and EvacTrain in the context of train evacuation modeling. Their results indicated that MassMotion, as a continuous-space microscopic model, provided more accurate and consistent evacuation time

predictions than discrete-network models. These findings support the credibility of MassMotion for high-fidelity passenger flow simulation in complex metro environments and reinforce its suitability for the evaluation of operational and structural optimization strategies in this research.

### 2.2 Framework for scenario optimization

As illustrated in Fig. 1, the dynamic optimization framework proposed in this study consists of three sequential stages. In the first stage, a detailed 3D model of Liyuan South Road Station is constructed, incorporating all key station elements—including fare gates, railings, staircases, escalators, elevators, and exit passages. This comprehensive spatial model is then imported into the pedestrian simulation software MassMotion, where a baseline simulation is conducted using preliminary parameter settings to establish reference conditions.

In the second stage, the model parameters are calibrated and refined using empirical field data collected from the station. This calibration ensures that the simulation results closely reflect actual passenger flow behavior. After adjustment, a second round of simulation is conducted to validate and confirm the reliability of the optimized parameter values, thereby enhancing the model's representational accuracy and predictive capability.

In the final stage, a series of optimized design scenarios—each representing different combinations of operational and structural interventions—are developed and simulated under varying passenger flow conditions. These simulations aim to assess the relative effectiveness of each scenario in mitigating congestion and improving passenger flow. Through this iterative process, the study achieves a dynamic and data-driven optimization of passenger flow strategies tailored to the specific context of a complex metro interchange station.

## 3 Simulation model construction and validation

### 3.1 Basic model construction and parameterization

To enhance the accuracy and realism of the simulation model, this study takes Ningbo Liyuan South Road Station

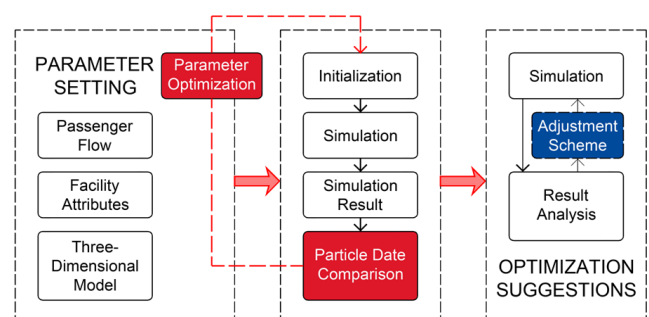


Fig. 1 Technical route of the study

as the case site and reconstructs detailed 3D models of key station areas, including the concourse, platforms, connecting corridors, fare gates, and entrances/exits. These models are developed based on construction drawings and on-site investigations. Passenger inflow and outflow boundary conditions are also defined according to observed entry and exit locations. Data collection was conducted from 08:00 a.m. to 08:30 a.m. on May 12, 2025 (Monday), a typical weekday morning peak period characterized by high passenger volume and pronounced congestion. This time window was chosen to capture critical bottlenecks and risk-prone nodes, providing a representative basis for long-term scenario analysis.

Simulation parameters—such as pedestrian walking speed distribution, average security check duration, and the capacity of escalators and fare gates—were obtained through field measurements or relevant design specifications. These parameters were further refined during the model calibration process to ensure alignment between simulated outputs and real-world conditions.

Passenger flow data were collected using a high-resolution camera positioned directly opposite the security screening area, offering a horizontal field of view that captured the full scope of pedestrian activity. The video was recorded at a resolution of  $2720 \times 2040$  pixels and a frame rate of 30 frames per second, providing sufficient granularity for accurate object detection and trajectory extraction.

To extract pedestrian trajectories with high precision, a YOLOv8 (Jocher, online) + ByteTrack (Zhang et al., 2022) detection and tracking system was implemented. A custom-trained YOLOv8 model (yolo11x.pt based on the Ultralytics framework) was employed for object detection, using a confidence threshold of 0.3 and an Intersection over Union (IOU) threshold of 0.6. ByteTrack was applied with default settings, including an IOU threshold of 0.5 for target association and a minimum initialization duration of 3 frames (Fig. 2). These parameters were selected to balance sensitivity and tracking stability.

Manual verification through spot checks confirmed that the detection and tracking process was robust, with no significant false positives, missed detections, or trajectory drift. Each pedestrian was assigned a unique trajectory ID, and dwell times were recorded to compute walking speeds and durations at key checkpoints. These trajectory datasets served as critical inputs for the calibration and execution of the MassMotion simulation model.

Automated video analysis significantly enhances the efficiency of data processing in pedestrian flow studies. However, in order to ensure the accuracy and reliability of

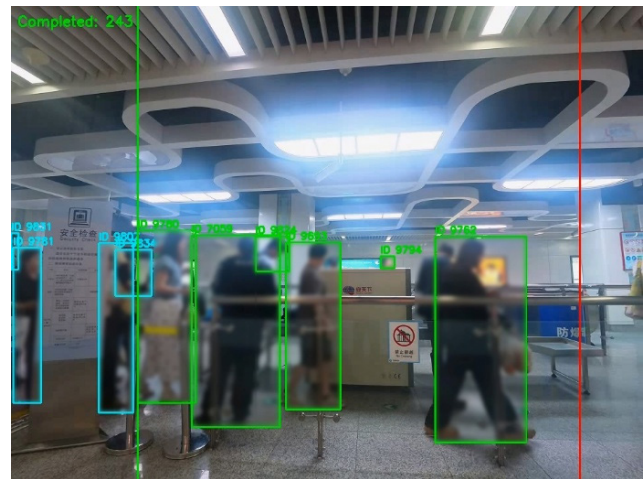


Fig. 2 Screenshot of YOLO+ByteTrack detection

the extracted data, the algorithm outputs were subjected to manual cleaning and calibration. Specifically, repeated appearances by station staff, individuals briefly captured from non-paid areas, and fragmented trajectories resulting from identity switching due to occlusion were carefully removed. After data cleaning, a total of 456 valid passenger samples were obtained for further analysis.

The distribution of security-check durations for these valid samples is presented in Fig. 3. The results exhibit a distinct triple-peaked pattern, corresponding to three typical categories of screening speeds: fast (passengers without bags), slow (passengers with small bags), and super-slow (passengers carrying bulky luggage). This empirical distribution was used to configure the security-check parameters in the simulation model, as detailed in Table 1.

In addition, field observations revealed that whether a passenger carried luggage had a negligible impact on ticket gate processing time. Accordingly, the ticket gate delay was simplified in the simulation as a constant value of 2 s per passenger. The speed of escalators was set to 0.65 m/s in accordance

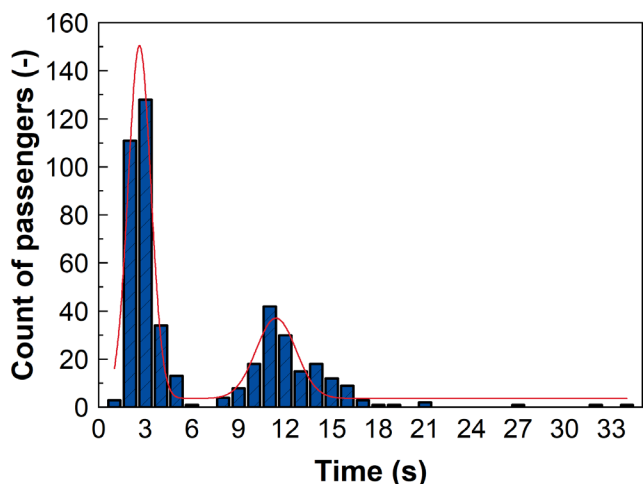


Fig. 3 Distribution of passenger security-check durations

**Table 1** Parameters for security check behavior

| Screening category              | Sample size | Mean (s) | Std. dev. (s) | Min (s) | Max (s) |
|---------------------------------|-------------|----------|---------------|---------|---------|
| Fast (no bag)                   | 290         | 3        | 1             | 2       | 6       |
| Slow (with bag)                 | 161         | 12       | 2             | 8       | 19      |
| Super-slow (with bulky luggage) | 5           | 27       | 5             | 21      | 34      |

with standard design specifications (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013).

Based on field observations, security check durations were classified into three distinct categories and input into the "link" node settings within MassMotion, along with their empirically observed proportions. This approach ensures that the simulation realistically captures the temporal characteristics of the security-screening bottleneck, which plays a critical role in shaping congestion dynamics in the station entry area.

Accurate parameter configuration is essential not only for ensuring the internal validity of the simulation model but also for guaranteeing the external reliability of its outputs—particularly when such outputs inform practical planning and operational decisions. For instance, if the average security-check duration is underestimated, the model will misrepresent key performance indicators such as queue lengths, local crowd density, and waiting times in the screening area, leading to an underestimation of congestion risk. Escalator speed is another sensitive parameter: a reduction in vertical transport speed delays the dispersal of passengers from platform to concourse levels, thereby increasing the likelihood of crowd buildup and queuing on the platform. Similarly, the distribution of pedestrian walking speeds affects overall flow rhythm, transfer durations, and spatiotemporal crowd density. Lower average walking speeds result in longer dwell times within the station, which in turn raise instantaneous population density and exacerbate peak-period congestion.

Given the significance of these factors, the parameter tuning process focused closely on their influence over localized congestion intensity, the distribution of travel times, and patterns of passenger accumulation throughout the station. During the model calibration stage, iterative adjustments were made by comparing simulation outputs with empirical data, ensuring that the model's responses accurately reflect observed passenger flow behavior under real-world operating conditions.

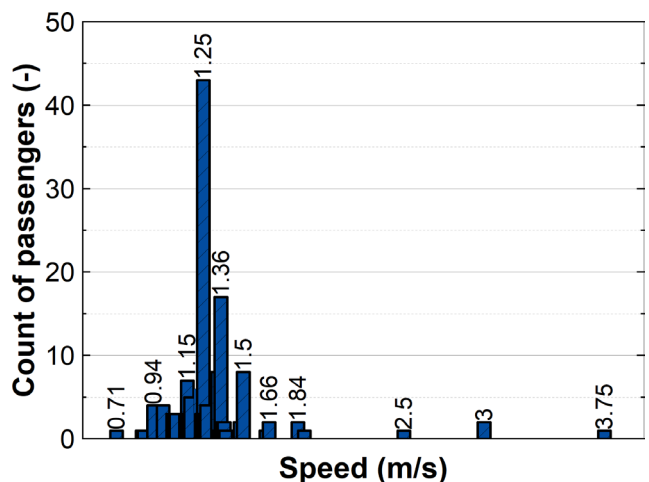
### 3.2 Model validation

The validity of the simulation model forms the foundation for the reliability and credibility of the study's conclusions. To verify the model's accuracy, a validation test was conducted following the observation-simulation comparison validation framework proposed by Yao (2008), using Entrance Corridor C at Liyuan South Road Station. This corridor was selected due to its relatively straight and flat geometry, which minimizes the influence of external structural factors and facilitates accurate observation of pedestrian behavior.

Video footage of pedestrian movement within the corridor was collected during the weekday morning peak period on Thursday, June 12, 2025, from 08:00 a.m. to 08:30 a.m. The selected corridor segment measures 6 m in length and 5.5 m in width. Pedestrian detection and tracking were performed using the YOLO (Jocher, online) algorithm for object identification and ByteTrack (Zhang et al., 2022) for multi-object tracking. The resulting pedestrian counts were manually cross-validated to ensure high detection accuracy.

A total of 147 valid pedestrian trajectories were obtained from the video data, including 92 individuals entering and 55 exiting the corridor. The walking speed distribution derived from these samples is presented in Fig. 4. The observed average pedestrian speed was 1.31 m/s, which served as a key reference for calibrating walking speed parameters in the simulation model.

The pedestrian walking speed within the simulation model was configured to follow MassMotion's default normal distribution, characterized by a mean speed of 1.35 m/s, a standard deviation of 0.25 m/s, a maximum speed of 2.05 m/s, and a minimum speed of 0.65 m/s (Laxman et al., 2010; Teknomo, 2016; Weidmann, 1993). To evaluate the model's performance, simulations were conducted for corridor lengths of 50 m, 100 m, 200 m, 400 m, and 800 m, and the



**Fig. 4** Measured pedestrian speed distribution

corresponding average pedestrian speeds were computed for each case. The relative errors between simulated and observed speeds are summarized in Table 2.

A comparison of the observed pedestrian speed distribution (Fig. 4) and the relative error analysis (Table 2) demonstrates close agreement between the simulation results and field measurements. These findings indicate that the model effectively reproduces pedestrian speed characteristics and thus possesses a high degree of validity for representing real-world pedestrian movement within the station environment.

Despite the satisfactory calibration outcomes, the simulation results remain subject to various sources of uncertainty. These primarily include:

1. uncertainties inherent in the input data, such as errors in passenger flow forecasts and the intrinsic variability and stochasticity of individual passenger behavior parameters;
2. uncertainties arising from the model's inherent simplifying assumptions, notably the use of a simplified social force model that may not fully capture the complexity of crowd dynamics in all situations.

To mitigate these uncertainties and enhance the model's stability and reliability, validation was performed using comprehensive field observation data. Furthermore, the adaptability and robustness of the proposed optimization scenarios were systematically evaluated through a series of passenger flow stress tests, as detailed in Section 4.5. These measures help ensure that the model's predictions remain credible across a range of realistic operating conditions.

For future research, conducting a thorough parameter sensitivity analysis is recommended to examine how variations in passenger behavioral parameters or arrival rate patterns influence simulation outcomes. Such analysis would provide a more comprehensive assessment of the model's robustness and inform the development of more resilient and adaptive passenger flow management strategies.

**Table 2** Statistical summary of simulation data for passageways at Liyuan South Road Station

| Simulated Corridor Length (m) | Simulated Avg. Speed (m/s) | Relative Error (%) |
|-------------------------------|----------------------------|--------------------|
| 50                            | 1.16                       | 11.45%             |
| 100                           | 1.18                       | 9.92%              |
| 200                           | 1.18                       | 9.92%              |
| 400                           | 1.20                       | 8.40%              |
| 800                           | 1.23                       | 6.11%              |

## 4 Simulation analysis and optimization evaluation

### 4.1 Scenario setting and evaluation index

#### 4.1.1 Research background and passenger flow scenarios

Liyuan South Road Station functions as a key interchange hub within the Ningbo Metro network, connecting Line 2 on the second basement level with Line 8 on the third basement level. The station is situated in an area characterized by mixed land uses, including residential, commercial, and educational facilities. It serves as a critical transfer point for passengers traveling to major destinations such as the airport, railway station, long-distance bus terminal, scenic spot, and central urban districts along these transit lines. The interchange corridor, with a width of only 6 m, often experiences high volumes of intersecting passenger flows, creating a spatial bottleneck that significantly constrains passenger movement and contributes to congestion risk.

In this study, the distant morning peak period was selected as the primary simulation scenario. According to the Line 2 Passenger Flow Forecast Report (Ningbo Urban Planning & Design Institute, 2010), peak passenger flow data are provided for the initial (2018), near-term (2025), and long-term (2040) periods, while the Line 8 Passenger Flow Forecast Report (Ningbo Urban Planning & Design Institute, 2022) includes projections for the initial (2029), near-term (2036), and long-term (2051) periods. Given the extended horizon and high uncertainty associated with the 2051 forecast, this study adopts a combined scenario utilizing the long-term (2040) peak passenger flows for Line 2 and the near-term (2036) peak flows for Line 8, which are temporally proximate. The mere four-year difference between these periods balances the forward-looking perspective of the "future" scenarios with the need for credible and actionable predictions.

The forecast data indicate that during the morning peak, a substantial majority of Line 8 passengers exit in the north-to-south direction, while a similarly large proportion of Line 2 passengers exit east-to-west. Moreover, transferring passengers constitute a significant portion of the total flow (Table 3). Passenger movements entering and exiting the station are predominantly concentrated at Exit B and Exit C (Fig. 5). This spatial distribution highlights potential operational challenges, including heavy passenger pressure on exit flows and limited capacity within the 6-m-wide interchange corridor, which may exacerbate congestion and safety risks.

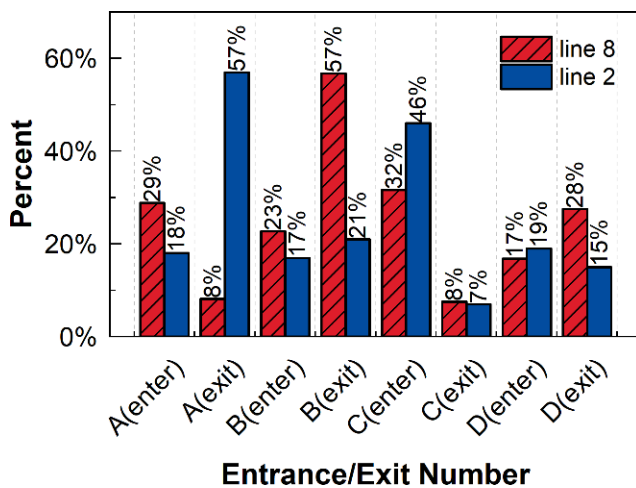
#### 4.1.2 System of evaluation indicators

In order to comprehensively assess the operational efficiency and safety risk of the Liyuan South Road Station under long-term peak passenger flow conditions, we have established

**Table 3** Passenger flow in and out of Liyuan South Road Station during morning peak

| Flow direction                   | Forecast volume ( $p/h$ ) | Percentage |
|----------------------------------|---------------------------|------------|
| Line 8 north to south inbound    | 733                       | 4.33%      |
| Line 8 north to south outbound   | 4,714                     | 27.88%     |
| Line 8 south to north inbound    | 1,004                     | 5.94%      |
| Line 8 south to north outbound   | 316                       | 1.87%      |
| Line 2 west to east inbound      | 951                       | 5.62%      |
| Line 2 west to east outbound     | 520                       | 3.07%      |
| Line 2 east to west inbound      | 225                       | 1.33%      |
| Line 2 east to west outbound     | 3,072                     | 18.17%     |
| Northbound to Westbound transfer | 620                       |            |
| Northbound to Eastbound transfer | 1,042                     |            |
| Southbound to Westbound transfer | 648                       |            |
| Southbound to Eastbound transfer | 1,384                     |            |
| Westbound to Northbound transfer | 500                       | 31.79%     |
| Westbound to Southbound transfer | 491                       |            |
| Eastbound to Northbound transfer | 127                       |            |
| Eastbound to Southbound transfer | 564                       |            |

Note:  $p$  stands for passengers, and  $h$  stands for hour



**Fig. 5** Passenger flow distribution ratio (long-term morning peak)

a multi-dimensional indicator system, which consists of the following four categories of core indicators:

1. Maximum passenger density: identifying extreme congestion points and structural bottlenecks.
2. Average passenger density: identifying sustained congestion areas (threshold set at 2.174 persons/m<sup>2</sup>).

**Table 4** Fruin's pedestrian level-of-service criteria (Fruin, 1971)

| Color  | LOS | Density ( $p/m^2$ )    | Area per person ( $m^2/p$ ) |
|--------|-----|------------------------|-----------------------------|
| Blue   | A   | $d \leq 0.309$         | $a \geq 3.24$               |
| Cyan   | B   | $0.309 < x \leq 0.431$ | $3.24 > x \geq 2.32$        |
| Green  | C   | $0.431 < x \leq 0.719$ | $2.32 > x \geq 1.39$        |
| Yellow | D   | $0.719 < x \leq 1.075$ | $1.39 > x \geq 0.93$        |
| Orange | E   | $1.075 < x \leq 2.174$ | $0.93 > x \geq 0.46$        |
| Red    | F   | $2.174 < x$            | $0.46 > x$                  |

Note:  $p$  stands for persons;  $d$  represents Density;  $a$  represents Area per person.

3. LOS (level of service) and count of LOS F congested passengers: evaluating worst-case crowding exposure based on Fruin's criteria. (Table 4)
4. OD (origin-destination) travel times: measuring the average and variability of entry, exit, and transfer times to gauge optimization effects.

Based on the above index system, a quantitative comparative analysis and congestion risk assessment of the simulation results of the original design scenario and the three optimization scenarios are carried out.

#### 4.2 Evaluation of the original program

Under the original scenario, MassMotion was used to construct a 3D simulation model of Liyuan South Road Station and input the calibrated long-term morning peak passenger flow forecast data (Table 3) and the passenger flow distribution ratio (Fig. 5) for simulation.

Referring to the study of Miao and Pan (2017), the metro train stopping time can be expressed by Eq. (1):

$$T = \frac{Q \cdot t}{nmd} + t_o + t_c - t_{\Delta} \tag{1}$$

In Eq. (1):

- $T_2$  is the dwell time of Line 2 trains,
- $T_8$  is the dwell time of Line 8 trains,
- $Q$  is the maximum one-way boarding and alighting passenger volume during the peak hour,
- $t$  is the average time for a single passenger to board or alight,
- $n$  is the number of trains operating during the peak hour,
- $m$  is the number of cars per train set,
- $d$  is the number of doors per side per car,
- $t_o$  is the door opening time,
- $t_c$  is the door closing time,
- $t_{\Delta}$  is the overlapping time between door operation and passenger boarding.

During the peak hour, the platform boarding and alighting volume at Liyuan South Road Station reaches 9,389 passengers for Line 8 and 6,044 passengers for Line 2. The trains are composed of Type B metro cars in 6-car formations, with 4 doors per car. The operating headway is 24 trains per hour (i.e., 2 min and 30 s between departures). Under typical conditions, the average boarding and alighting time per passenger is 0.7 s. The door opening time  $t_o$  is set to 8 s, the door closing time  $t_c$  is 15 s, and the overlapping time between door operations and boarding  $t_{\Delta}$  is 3 s.

Accordingly, the calculated dwell time is  $T_8 = 31.41$  s for Line 8 and  $T_2 = 27.35$  s for Line 2. In the simulation, these dwell times are rounded and set to  $T_8 = 31$  s and  $T_2 = 27$  s, respectively.

The simulation model input parameters are calibrated based on the above data to ensure that the simulation is close to the actual situation.

The simulation results of the original scenario (Fig. 6 (b)) reveal that several critical areas experience LOS F congestion during peak hours. Notably, these include the transfer corridor connecting the two lines, located in the middle of the Line 2 concourse level, the exit gate area on the southern side of the Line 8 concourse level, and the escalator entrances located approximately at axis 5 on the Line 8 platform level.

Regarding average passenger density (Fig. 6 (c)), multiple locations are classified as LOS E congestion areas. These include: all stairway and escalator entrances on the Line 2 concourse level; the down-escalator entrance at axis 2 on the Line 8 concourse level; the stairway and escalator entrances at axis 5 on the Line 8 platform level; and the escalator entrances at axis 8 on that same platform level. This indicates that, even under average flow conditions, the critical vertical transportation facilities are subject to sustained passenger pressure in the original scenario.

The primary factors contributing to this situation are:

1. The total capacity of vertical transportation facilities is insufficient to accommodate peak passenger volumes.
2. The spatial layout of these facilities fails to effectively disperse passenger flows, resulting in excessive concentration in specific channels or nodes and localized access pressure.
3. The intertwining and conflict of interchange and inbound/outbound passenger flow lines within the constrained space of the station concourse—such as the central area of the Line 2 concourse—further exacerbate congestion.

The areas exhibiting LOS E congestion represent significant safety hazards within the station and constitute major bottlenecks that adversely affect passenger experience and access efficiency. Consequently, the development and evaluation of targeted optimization scenarios addressing these bottlenecks is imperative to improve overall station performance.

### 4.3 Optimized scenario design

#### 4.3.1 Scenario 1: operational adjustments only

Scenario 1 (Fig. 7 (a)) optimizes passenger circulation through a set of operational adjustments. The key modifications target five areas:

- *Gate*: On the Line 8 concourse, inbound and outbound gates were swapped to better balance flows. Seven additional exit gates were installed—three between axes 3–4, one between 5–6, and three between 6–7—to more quickly alleviate congestion driven by heavy outbound volumes.
- *Elevator*: The Line 8 elevator was reoriented to open toward the south side to reduce conflicts between passenger flow paths and the reconfigured exit gates.
- *Escalator*: The up and down escalators at axis 8 on Line 8 were swapped to prevent flow conflicts introduced by the gate reconfiguration.
- *Stair*: The centrally located staircase on the Line 2 concourse was set to up-only operation during peaks. This intervention is designed to minimize congestion by separating transfer passengers from those entering and exiting Line 2 within this critical concourse area.
- *Isolation Railing*: Physical barriers were installed at strategic points to regulate flows and reduce congestion near escalator openings. Locations included: (i) the entrances to the up and down escalators on the Line 2 platform level; (ii) the area between the up and down escalators on the Line 8 platform level (axes 5–6); (iii) the west side of the Line 8 platform level (axes 10–11); and (iv) the junction of the transfer passage with the Line 8 concourse.

These operational adjustments collectively aim to streamline passenger circulation, mitigate flow conflicts, and reduce congestion at known bottlenecks within the station.

The simulation results (Fig. 7 (b) and 7 (c)) indicate that Scenario 1 markedly alleviates congestion in several critical areas, including the central region of the Line 2 concourse, the transfer corridor entrance connecting the two lines' concourses, and the southern exit gate area of the Line 8 concourse, all achieved without any structural

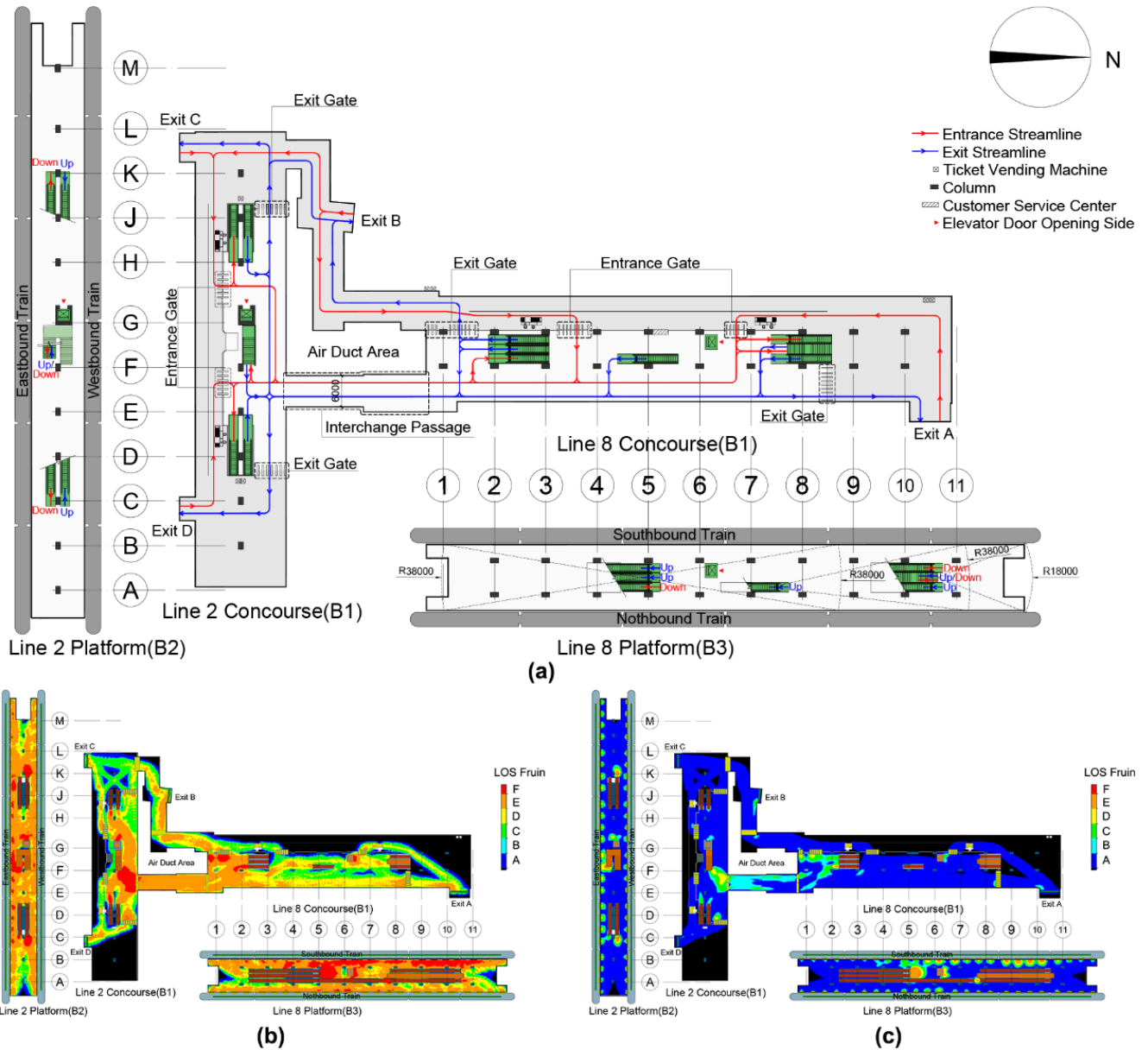


Fig. 6 Original scenario: (a) Passenger flow streamlines; (b) Maximum density map; (c) Average density map

modifications. Nevertheless, LOS F congestion persists in certain locations, with only marginal improvement observed at the mid-platform escalator (axis 5) on Line 8.

Overall, the operational adjustment measures implemented in Scenario 1 contribute to improved passenger flow in targeted areas and reduce conflict points at key nodes, particularly mitigating pressure in the central concourse and the Line 2 transfer corridor junction. However, congestion within vertical transport channels, driven by the simultaneous arrival of trains, remains largely unresolved by operational adjustments alone. The persistent mismatch between vertical transport capacity and passenger demand underscores the inherent limitations of relying exclusively on operational measures to address congestion challenges in complex interchange stations.

While operational adjustments are cost-effective and can be flexibly deployed in the short term, their potential for alleviating congestion is constrained by the fixed physical layout of the station. Consequently, some high-density segments only experience temporary or partial relief. Future efforts could explore integrating intelligent monitoring systems with dynamic scheduling mechanisms to enable more precise crowd management and guidance strategies. Such approaches would enhance the system's responsiveness to sudden passenger flow surges, thereby improving overall operational resilience and passenger safety.

#### 4.3.2 Scenario 2: Structural modifications only

Scenario 2 (Fig. 8 (a)) focuses on optimizing passenger flow distribution through targeted structural modifications. The two primary interventions include:

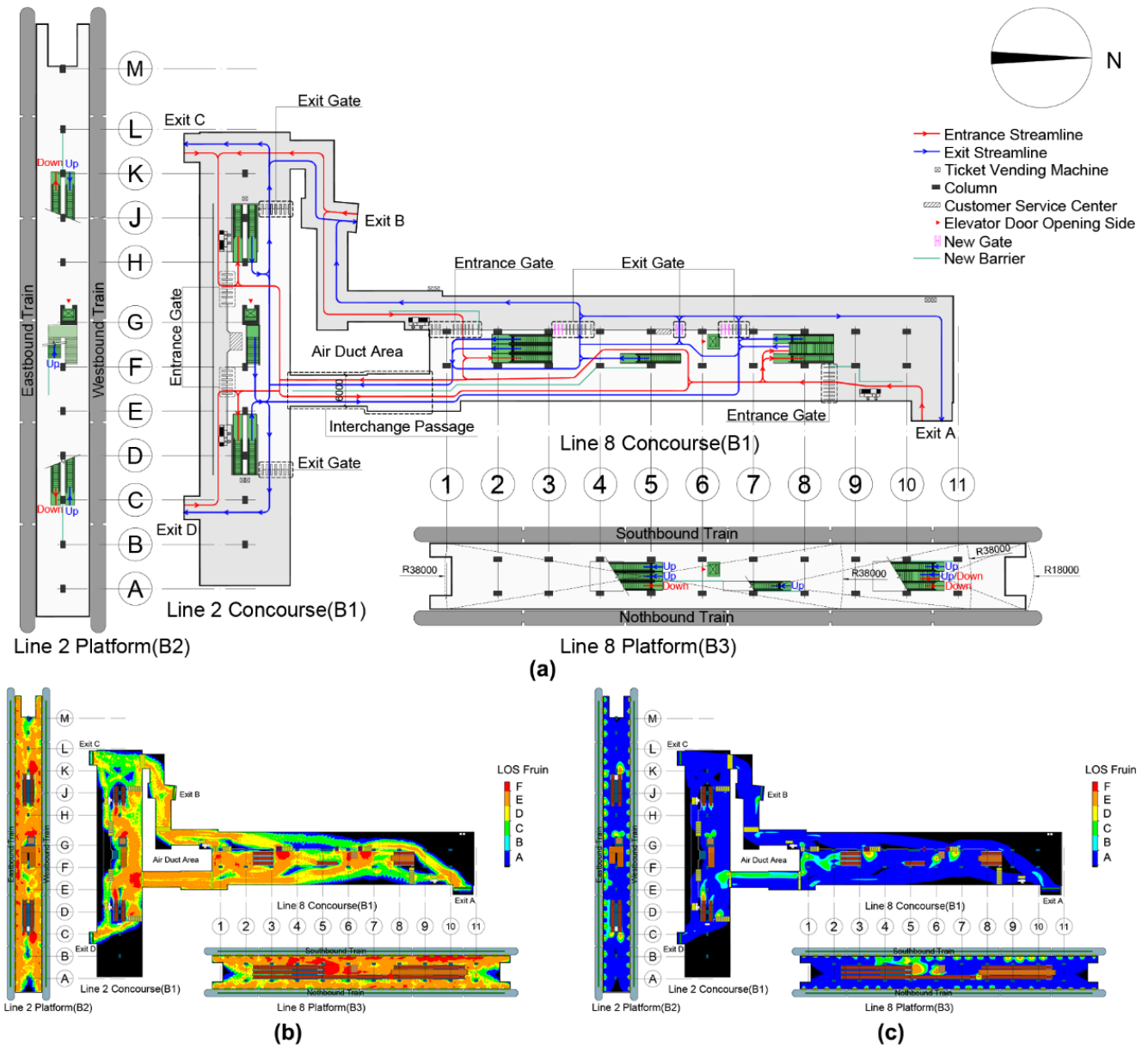


Fig. 7 Scenario 1: (a) Passenger flow streamlines; (b) Maximum density map; (c) Average density map

- *Transfer Channel Widening:* The transfer corridor connecting Line 8 and Line 2 is redesigned with a flared (trumpet-shaped) entrance. This geometric modification aims to reduce passenger flow pressure concentrated in the central area of the Line 2 concourse by facilitating smoother dispersion of transferring passengers.
- *Northward Platform Shift:* The platform of Line 8 is shifted northward by 19.525 m—approximately the length of one train car—to expand the effective service area of vertical transportation facilities at the northern end of the platform. This adjustment is designed to alleviate congestion by preventing excessive passenger accumulation at the southern end of the station.

Importantly, this shift minimizes disruptions to platform screen doors during reconstruction. Post-shift, the northern extremity of the Line 8 platform lies within 50 m of the farthest stairway entrance, thereby complying with relevant design codes and standards (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018).

These structural modifications aim to fundamentally enhance passenger flow distribution and vertical transport efficiency, addressing bottlenecks that operational adjustments alone cannot fully resolve.

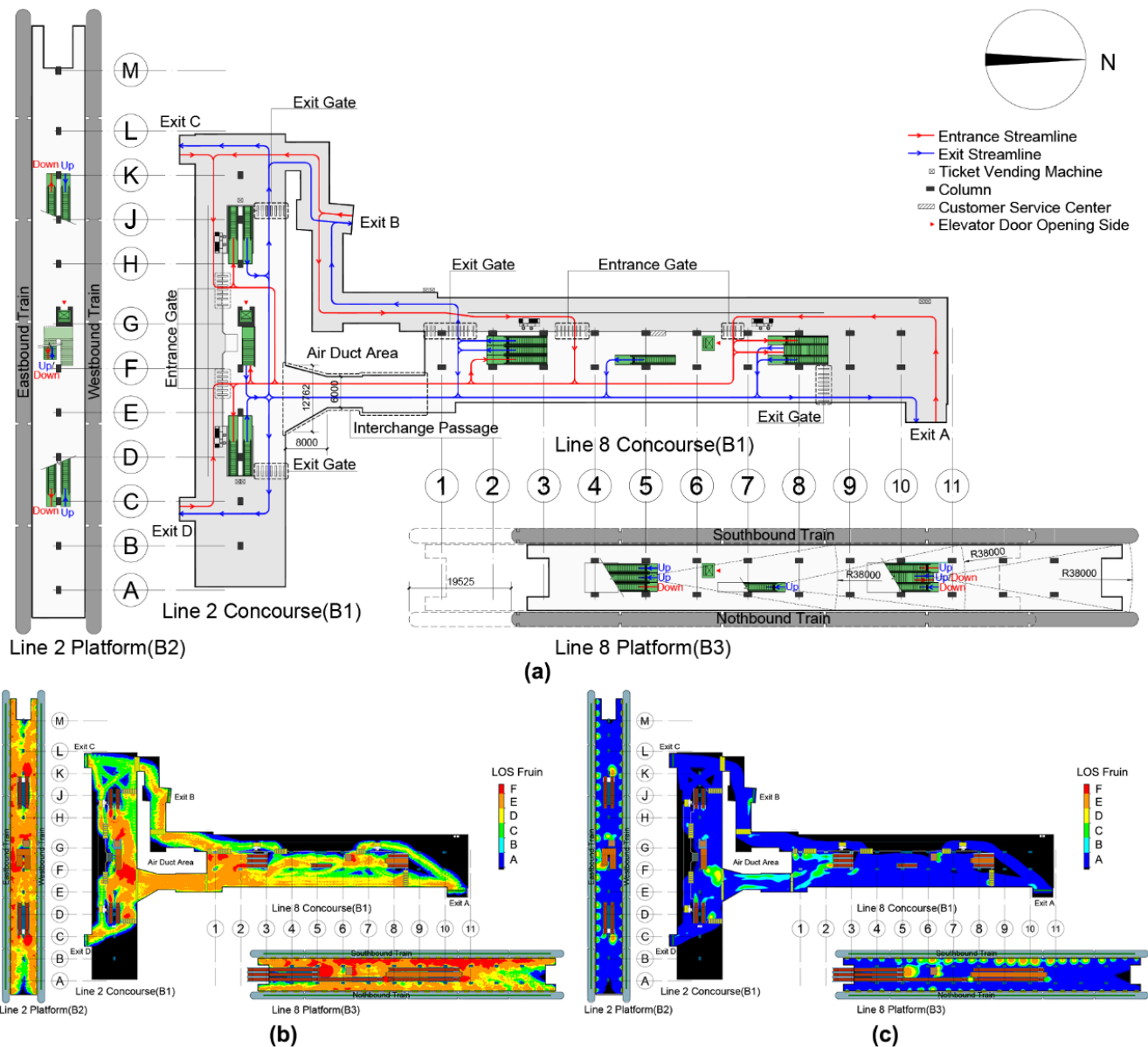


Fig. 8 Scenario 2: (a) Passenger flow streamlines; (b) Maximum density map; (c) Average density map

The simulation results (Fig. 8 (b) and 8 (c)) demonstrate that Scenario 2 markedly reduces passenger density within the transfer corridor and on the Line 8 platform. However, owing to the predominance of passengers exiting Line 8 in the north-to-south direction, the area adjacent to the exit gates on the southern side of the Line 8 concourse continues to experience LOS F congestion.

The implemented structural modifications have significantly enhanced spatial accessibility and promoted a more balanced distribution of passenger flows. Specifically, the widening of the interchange corridor into a flared, trumpet-shaped configuration effectively disperses passenger movements entering the Line 2 concourse, thereby mitigating congestion. Furthermore, shifting the Line 8 platform northward by 19.525 m extends the vertical transport

service coverage, alleviating pressure on escalators at the southern end of the station and reducing the overall average passenger density on the Line 8 platform. Nevertheless, congestion persists at the southern escalator entrance, with average densities remaining at LOS E levels.

These findings suggest that localized congestion will continue unless bottlenecks at critical nodes—such as escalator entrances—are directly addressed. This underscores the necessity of harmonizing station layout with facility capacity to optimize passenger flow. While structural interventions achieve substantial reductions in passenger density, particularly in spatially constrained zones, their extended implementation periods and potential operational disruptions limit their immediate applicability. Future research may consider the deployment of prefabricated or temporary

diversion structures to enhance the flexibility and efficacy of structural mitigation measures.

### 4.3.3 Scenario 3: Integrated optimization

Scenario 3 (Fig. 9 (a)) combines both operational management interventions and structural modifications to comprehensively optimize passenger flow organization and spatial distribution within the station. This integrated approach aims to leverage the synergistic effects of combining the flexibility of operational adjustments with the capacity enhancements afforded by structural changes. Essentially, Scenario 3 concurrently implements all the measures proposed in Scenarios 1 and 2 to achieve a more effective and holistic congestion mitigation strategy.

The simulation results (Fig. 9 (b) and 9 (c)) demonstrate that Scenario 3 is the most effective solution, substantially mitigating congestion in key areas such as interchange corridors, fare gates, and the Line 8 platform. This integrated scenario clearly exhibits synergistic effects: structural modifications provide an enhanced spatial framework for improved passenger distribution, while operational adjustments further streamline passenger flows, reducing conflicts between different movement streams and increasing the utilization efficiency of station facilities. For example, the northward shift of the Line 8 platform effectively disperses passenger flows, whereas the reconfiguration of fare gates—including the addition of extra exit gates and the repositioning of existing ones—directly enhances throughput at the southern exit bottleneck.

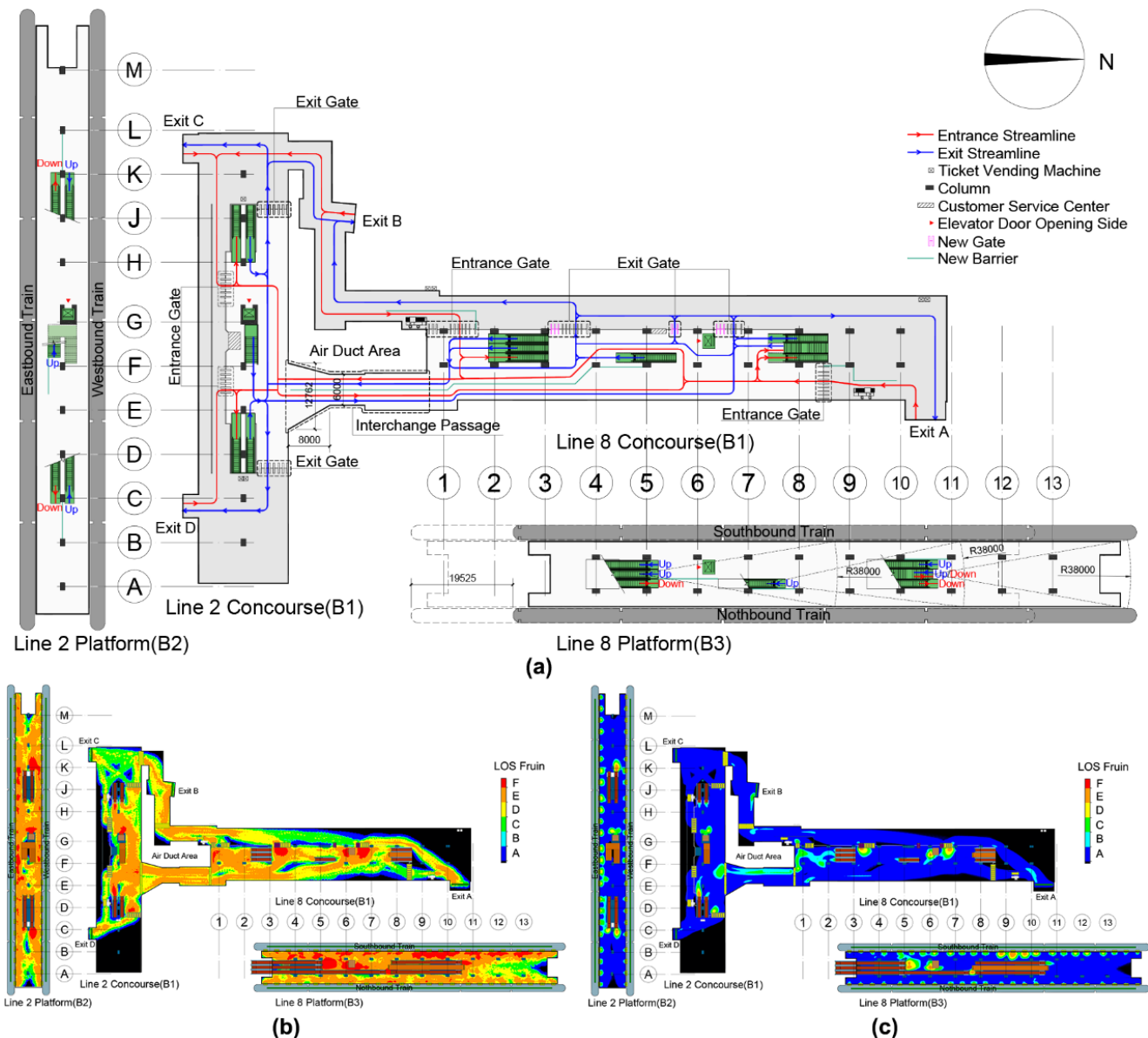


Fig. 9 Scenario 3: (a) Passenger flow streamlines; (b) Maximum density map; (c) Average density map

Overall, the combination of structural and operational measures facilitates smoother station operations and effectively controls passenger density at critical congestion points, underscoring the advantages of a comprehensive optimization approach in managing congestion risks at complex interchange hubs.

Although Scenario 3 outperforms the individual scenarios by optimizing multiple facets simultaneously, the specific integration of measures in this study relies primarily on expert judgment and lacks systematic algorithmic optimization. Future research should consider incorporating simulation feedback into optimization algorithms to develop intelligent recommendation systems capable of automatically generating and dynamically adjusting combinations of multiple strategies. Such developments would significantly improve the adaptability, robustness, and scalability of congestion management solutions in metro interchange stations.

#### 4.4 Summary of comparison of different scenarios

Fig. 10 shows substantial differences in aggregate passenger flow metrics across scenarios. Both Scenario 1 and Scenario 3 achieve reductions in average and maximum passenger densities within the station, with Scenario 3 yielding the most substantial improvements—namely, a 9.39% decrease in average density and a 2.31% reduction in maximum density. However, the optimization scenarios slightly increase average transfer times, primarily due to longer walking distances from rerouted passenger flows. This marginal increase in travel time is offset by notable gains in operational efficiency, passenger safety, and overall comfort. Consequently, congestion levels are markedly reduced, and the overall interchange experience is enhanced.

Station-level averages cannot fully capture spatial variability or the severity of localized congestion. To address this

limitation, eight congestion-prone zones (A1–A8, depicted in Fig. 11) were delineated based on the maximum density map of the original scenario. We then quantified average densities in these zones using the MassMotion "volume" function to provide a more granular assessment of critical risk points.

A comparative analysis of the eight identified congestion hotspots reveals distinct local effects among the optimization scenarios (Fig. 12). For instance, in the A1 and A3 regions, Scenarios 1 and 3 notably reduce congestion at the stairway entrances on the Line 2 platform level by designating the central stairs of the Line 2 concourse as one-way upward only. This operational control measure is particularly critical to accommodate anticipated increases in interchange traffic or outbound flows on Line 2 in the future.

In the A2 and A4 areas, the installation of isolation railings between the upward and downward escalators on the Line 2 platform level—implemented in both Scenarios 1 and 3—serves to increase separation between passengers entering and exiting escalators, thereby mitigating congestion at these vertical access points.

Regarding area A5, the addition of guide railings at the Line 8 station concourse level in Scenarios 1 and 3 effectively alleviates pressure near the upward escalator entrance on the southern side of the concourse.

In the A6, A7, and A8 areas, Scenarios 2 and 3 optimize the vertical access layout on the platform level, resulting in a more balanced passenger distribution between the north and south ends of the platform and preventing congestion buildup, especially within the A6 zone.

Further insights were obtained by analyzing different guide rail configurations in Scenario 3 (Figs. 13 and 14). It was found that guide railings should be positioned near the platform edge on the side experiencing the highest passenger volume and oriented toward the primary exit direction

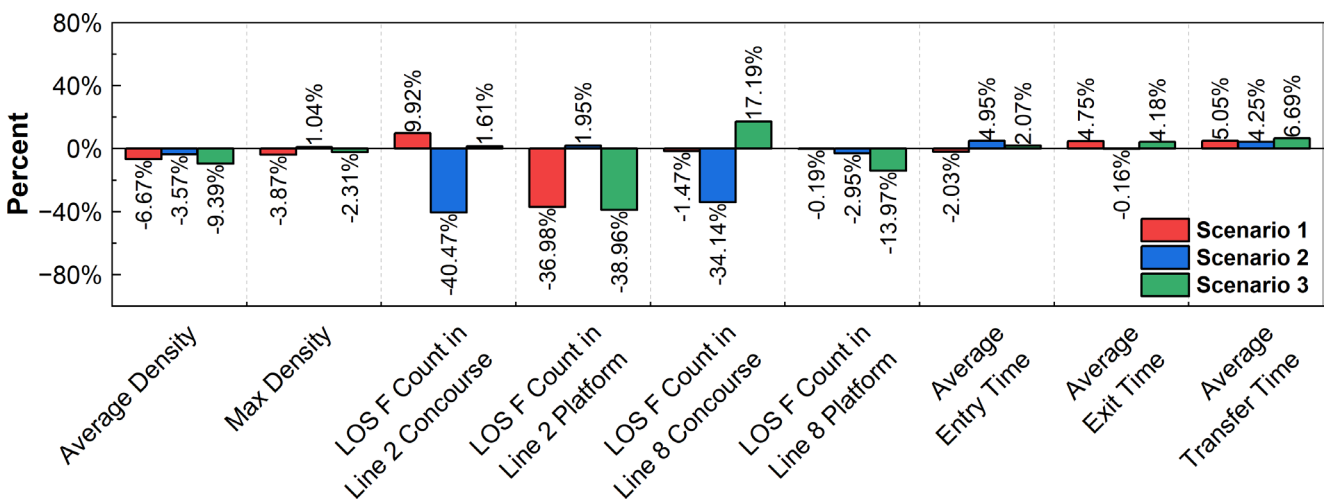


Fig. 10 Changes in service indicators

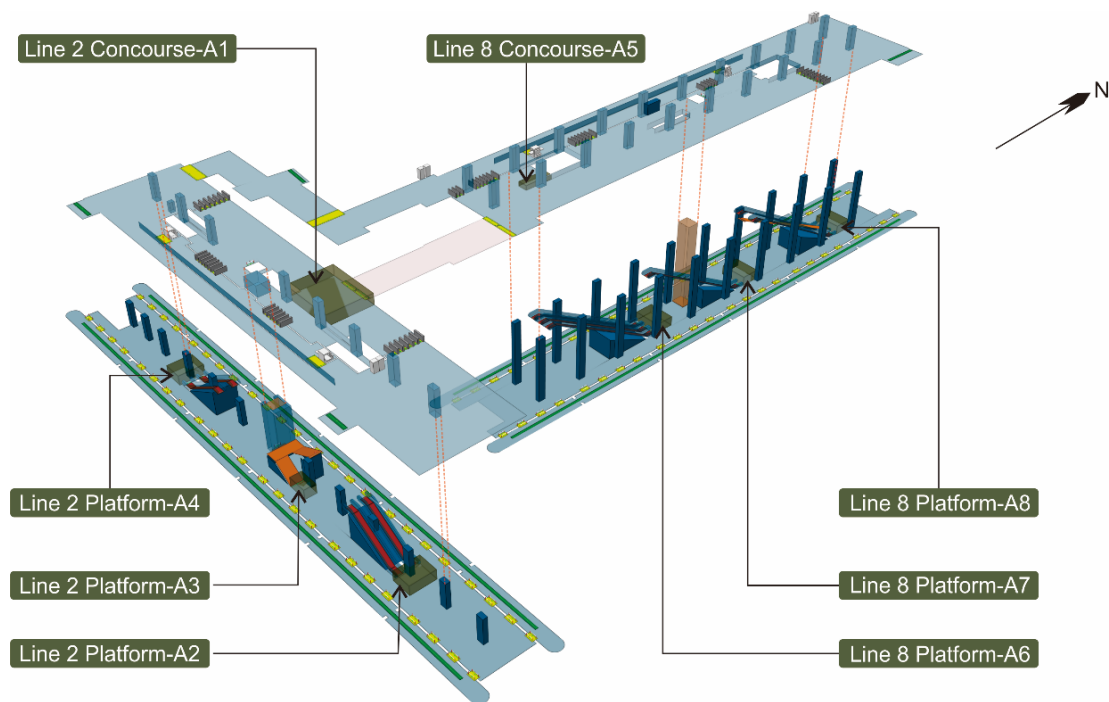


Fig. 11 Locations of potential congestion points during long-term morning peak

where disembarking passengers concentrate. This arrangement helps prevent large groups of disembarking passengers from directly impeding vertical access entrances (e.g., points A3-P1, A7-P1, and A8-P1). In locations where stairs and escalators are grouped, railings (e.g., A8-P1) should be installed on the side with heavier disembarking traffic to more effectively relieve vertical access pressure. Moreover, when upward and downward escalators are arranged in parallel, the introduction of railings between them effectively reduces the cross-flow interference of passengers entering and exiting the station. This effect has been empirically verified at platform-level hotspots A2 and A4 on Line 2, as well as at A6 on Line 8.

#### 4.5 Applicability and stress testing of different scenarios

To assess the applicability of the scenarios under varying passenger flow intensities, this section simulates a far-peak passenger surge scenario, with flow rates ranging from 1.1 to 1.7 times the base level. The corresponding adjusted train dwell times (Table 5) are calculated according to Eq. (1), while maintaining constant departure intervals. This approach facilitates a comparative analysis of station operational performance across different scenarios under progressively increasing passenger demand pressures.

Nelson and Mowrer (2002) demonstrated that when crowd density exceeds 3.8 persons/m<sup>2</sup>, pedestrian movement becomes severely restricted, increasing the risk of collective accidents such as stampedes due to insufficient

refuge space during unexpected events. Accordingly, this study adopts an average density threshold of 3.8 persons/m<sup>2</sup> to identify potential overcrowding risk.

To evaluate the performance of the proposed scenarios under varying passenger pressures, eight potential congestion hotspots (A1–A8) were analyzed for the duration during which their average densities exceeded this critical threshold. The results (Fig. 15) indicate that, for all scenarios, none of the eight hotspots surpass the 3.8 persons/m<sup>2</sup> limit at passenger flow levels between 1.0 and 1.2 times the base flow. Notably, area A6 under the original scenario is the first to exceed this threshold when passenger flow reaches 1.3 times the baseline. Detailed statistics of risk point exceedances are presented in Table 6.

The results (Fig. 15) indicate that when passenger volume reaches 1.3 times the base scenario, congestion pressure at each hotspot in the original scenario rises noticeably. At 1.4 times, Scenario 2 (infrastructure-only) is no longer able to effectively mitigate congestion. At 1.7 times, Scenario 1 (operations-only) sees some areas exceeding risk thresholds. Only Scenario 3 (comprehensive optimization) can effectively handle passenger flows up to 1.7 times and beyond.

#### 4.6 Analysis of operating costs and benefits

To quantitatively illustrate the cost–benefit trade-offs among the three optimization scenarios, approximate estimates of capital expenditure (CAPEX) and operating expenditure (OPEX) were developed based on engineering

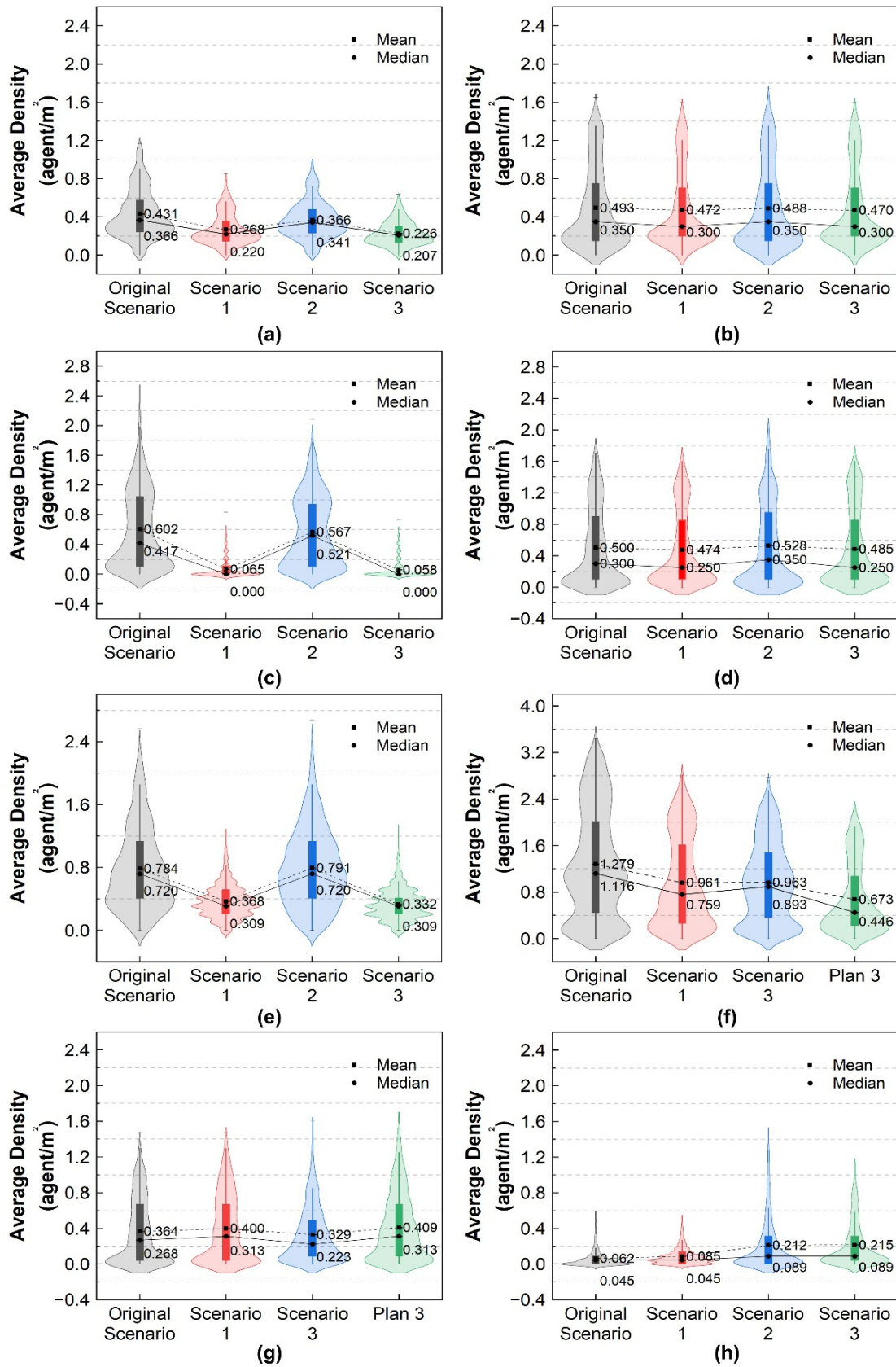


Fig. 12 Comparison of average density at potential congestion points during long-term morning peak: (a) Line 2 concourse-A1; (b) Line 2 platform-A2; (c) Line 2 platform-A3; (d) Line 2 platform-A4; (e) Line 8 concourse-A5; (f) Line 8 concourse-A6; (g) Line 8 concourse-A7; (h) Line 8 concourse-A8

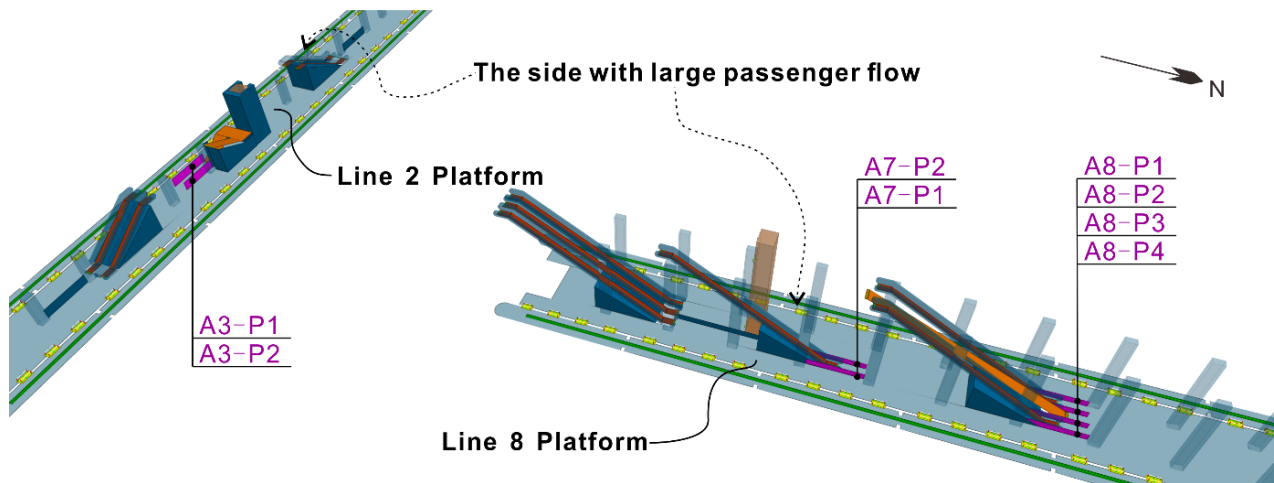


Fig. 13 Alternative railing positions in areas A3/A7/A8 (Scenario 1)

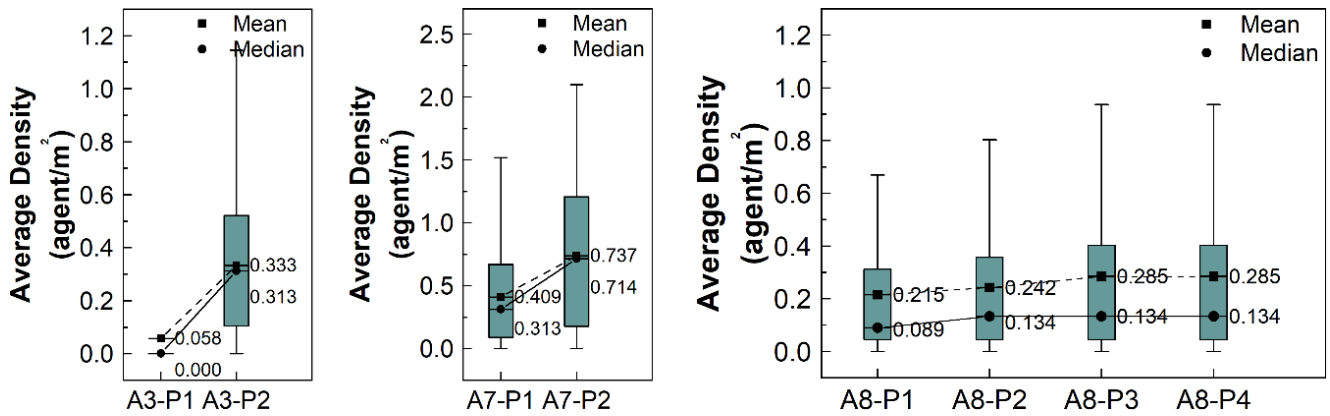


Fig. 14 Comparison of average density for different railing positions in areas A3/A7/A8 (Scenario 1)

Table 5 Train dwelling and door operation time

| Flow Multiplier | Line 8 (s) | Line 2 (s) |
|-----------------|------------|------------|
| 1               | 30         | 26         |
| 1.1             | 31         | 27         |
| 1.2             | 32         | 28         |
| 1.3             | 33         | 28         |
| 1.4             | 34         | 29         |
| 1.5             | 35         | 30         |
| 1.6             | 36         | 30         |
| 1.7             | 37         | 31         |

analogies and unit cost references for metro station retrofitting in Ningbo. Table 7 summarizes the cost composition and qualitative benefit evaluation for each scenario.

Scenario 1 (operations-only) involves no structural renovation and primarily depends on flow direction adjustments and staff guidance; thus, no additional capital investment is required. Its implementation relies on increased staffing for peak-hour management and minor adjustments to signage and control systems, resulting in negligible additional OPEX ( $< 5 \times 10^3$  CNY per month). The scenario provides localized and reversible improvements, offering a low-cost, short-term solution.

Scenario 2 (structural modifications only) entails civil and architectural reconstruction, including flaring of the transfer corridor, local renovation of finishes, and platform screen door relocation. The estimated civil works cost is approximately 430,000 CNY, with an additional 550,000 CNY for interior renovation and 400,000 CNY for platform screen door modifications. The total CAPEX is thus approximately 1.38 million CNY, representing a one-time investment that yields lasting improvements in spatial accessibility and passenger comfort. However, implementation may cause moderate construction disruption and requires temporary closure of local passage areas.

Scenario 3 (integrated optimization) combines the civil modifications of Scenario 2 with operational management interventions and additional equipment such as railings and signage. The estimated investment includes 430,000 CNY for civil works, 550,000 CNY for renovation, 14,000 CNY for railing installation, 18,000 CNY for minor equipment and accessories, and 400,000 CNY for platform screen door adjustment—totaling approximately 1.41 million CNY. The OPEX increases slightly due to additional monitoring and management (approx.  $10 \times 10^3$  CNY per year), but

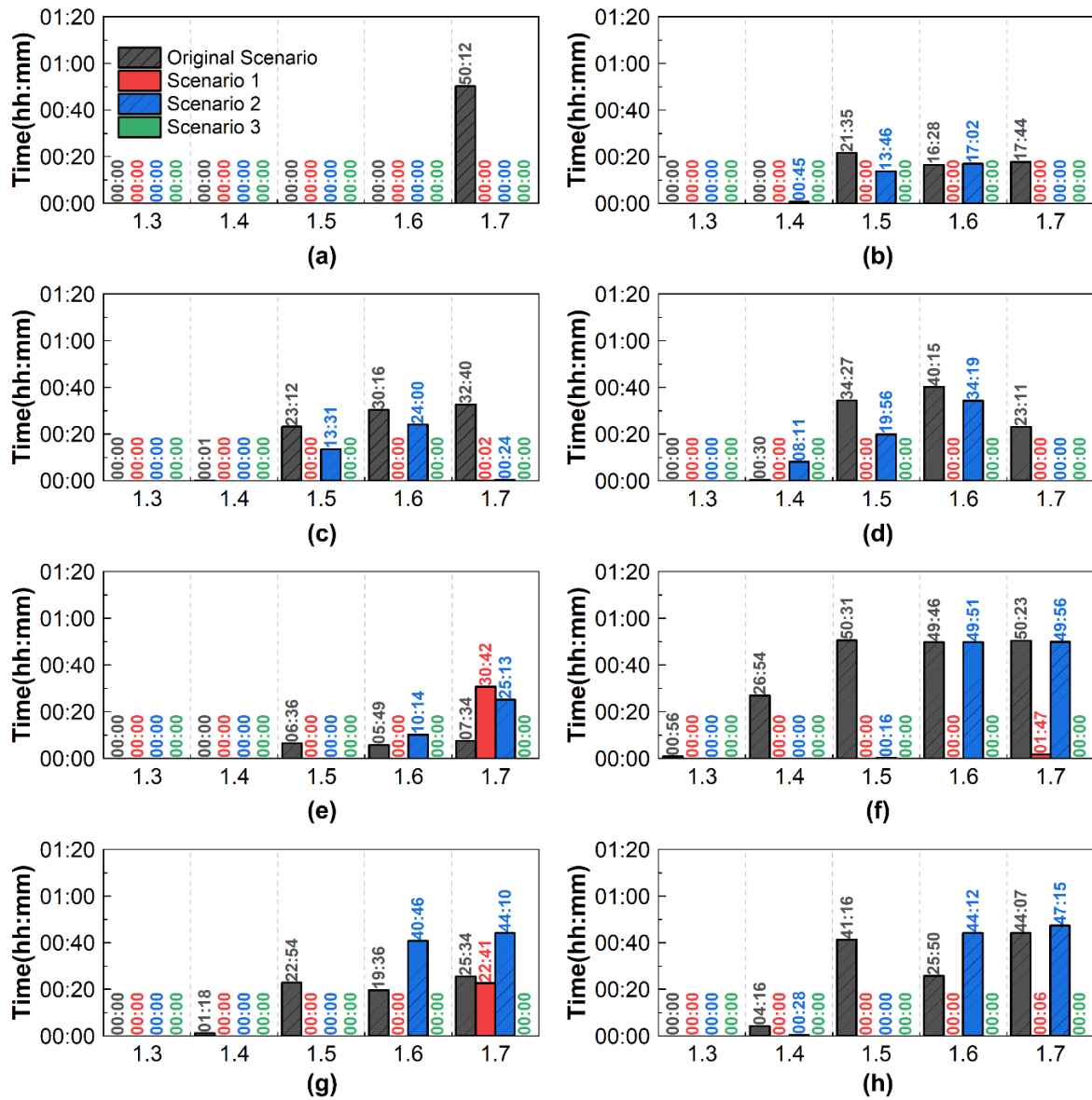


Fig. 15 Duration of congestion exceeding risk thresholds at potential congestion points: (a) Line 2 concourse-A1; (b) Line 2 platform-A2; (c) line 2 platform-A3; (d) line 2 platform-A4; (e) Line 8 concourse-A5; (f) Line 8 concourse-A6; (g) Line 8 concourse-A7; (h) Line 8 concourse-A8

Table 6 Statistics of identified risk points

| Scenario type     | Corresponding passenger flow multiplier at risk points | Affected areas       |
|-------------------|--|----------------------|
| Original Scenario | 1.3 ~ 1.7  | All                  |
| Scenario 1        | 1.7  | A3/A5/A6/A7/A8       |
| Scenario 2        | 1.4 ~ 1.7  | A2/A3/A4/A5/A6/A7/A8 |
| Scenario 3        | None   | None                 |

the combined scenario delivers the best cost-effectiveness, maintaining safe operating conditions even when passenger flows reach 1.7 times the design level.

### 5 Summary of optimization techniques for metro interchange stations (based on the case of Liyuan South Road Station)

Based on the simulation analyses and evaluation of optimization scenarios at Liyuan South Road Station, this section synthesizes key technical measures that can serve as valuable references for the planning, design, and renovation of similar metro interchange stations. These strategies aim to enhance transfer efficiency and mitigate congestion risks through an integrated approach combining spatial reconfiguration and operational management optimization.

**Table 7** Approximate investment and operating cost estimates for the three optimization scenarios

| Scenario Type                                | Main components   | Estimated CAPEX (CNY)      | Estimated OPEX impact (CNY) | Implementation difficulty | Construction disruption | Overall benefit and resilience   |
|--|---|----------------------------|-----------------------------|---------------------------|-------------------------|--|
| Scenario 1:<br>Operational adjustments only  | Flow direction control, signage optimization, staff management                        | $\approx 0$                | $+ < 5 \times 10^3$ / month | Very low                  | None                    | Quick, low-cost improvement; limited long-term effect                      |
| Scenario 2:<br>Structural modifications only | Corridor flaring (430 k), finish renovation (550 k), screen door modification (400 k) | $\approx 1.38 \times 10^6$ | None to low                 | High                      | High                    | Durable spatial improvement; moderate resilience ( $\leq 1.4 \times$ flow) |
| Scenario 3:<br>Integrated optimization       | Scenario 2 + railing (14 k), small equipment (18 k), operational coordination         | $\approx 1.41 \times 10^6$ | $+ 10 \times 10^3$ / year   | High                      | High                    | Comprehensive benefit; robust performance ( $\leq 1.7 \times$ flow)        |

### 5.1 Space structure optimization techniques

Numerous studies have demonstrated that a well-designed spatial layout forms the foundation for efficient passenger flow management. Through an in-depth analysis of the passenger flow challenges at Liyuan South Road Station, this study identifies and validates several spatial optimization techniques as follows.

**Optimization of channel design to enhance capacity:** Bottleneck areas such as interchange corridors can achieve significant capacity improvements by increasing their effective width. At Liyuan South Road Station, for example, the net width of the passage connecting the concourses of the two lines has been progressively expanded from 6 m near one end of the Line 2 concourse to a flared opening, with the intersection width increased from 6 m to approximately 12.8 m (further detailed dimensioning to be refined in subsequent design stages). This spatial adjustment effectively cushions the convergence of passenger flows, reduces density pressure in the interchange area (Zone A1), and enhances passenger comfort and transfer efficiency. The extent and dimensions of such channel widenings should be precisely calibrated based on projected passenger volumes, targeted service levels, and site-specific constraints.

**Adjusting functional area layouts to balance passenger flow distribution:** In locations where passenger flows are highly concentrated—such as platform levels—the optimization of vertical transportation facility layouts is essential to achieve a more balanced spatial distribution of passengers. At Liyuan South Road Station, the northward shift of the Line 8 platform by approximately one train car length (19.525 m) through structural modifications, accompanied by the coordinated relocation of platform slabs, platform screen doors, and related infrastructure, has expanded vertical access coverage at the platform's northern end. This spatial reconfiguration guides passengers to utilize station facilities more evenly, mitigating excessive

concentration at specific nodes (e.g., Zone A6) and thereby lowering overall flow density and congestion risk.

### 5.2 Operations management optimization techniques

Building upon spatial structure optimizations, the adoption of refined operational and management strategies can further enhance station operational efficiency as well as safety and security levels.

**Optimization of vertical traffic operation modes:** During morning and other peak passenger flow periods, a cost-effective and impactful strategy is to adjust the directionality of staircases and escalators to accommodate predominantly unidirectional flows. Through origin-destination (OD) analysis and simulation, dominant one-way vertical transportation facilities during peak hours can be identified and configured for unidirectional operation to effectively reduce passenger conflicts. For instance, at Liyuan South Road Station, this measure significantly alleviated congestion density in Zone A3. Nevertheless, potential impacts on reverse passenger flows must be carefully assessed and managed to prevent the formation of new bottlenecks.

**Optimization of AFC system layout and management:** Adjusting the arrangement and functional configuration of Automated Fare Collection (AFC) gates according to passenger flow characteristics enables station capacity to better match demand, accelerating passenger evacuation and relieving localized congestion. At Liyuan South Road Station, the reconfiguration involved swapping the positions of certain entry and exit gates and increasing the number of exit gates on Line 8. Although these adjustments may slightly increase travel distances for some passengers, the resulting smoother passenger flows, reduced queue lengths, and improved safety perceptions more than compensate for this, thereby enhancing the overall passenger experience.

**Installation of crowd guidance facilities:** Placement of guiding structures such as railings and barriers should

be informed by simulation results and on-site observations, focusing on critical nodes prone to conflicts or congestion—e.g., stairway and escalator entrances in Zones A2–A4 and A6–A8, as well as key corridor intersections. The principal objectives are to separate opposing flows, regulate queuing behavior, and channel pedestrian movement efficiently. For island platforms, consideration of the spatial distribution of alighting passengers is important; positioning railings on the side with concentrated alighting flow has proven more effective in guiding pedestrian traffic.

Finally, the effectiveness of these diversion and management measures must be validated through further simulation and field observations. Evaluation metrics should include passenger density, queue lengths, changes in walking speeds, conflict mitigation, and the identification of any newly emerging bottlenecks within the target areas. Quantitative analysis of these indicators provides an evidence-based foundation for verifying optimization efficacy and supports continuous refinement of the implemented strategies.

## 6 Limitations and future work

While this study provides a robust framework for evaluating optimization strategies, it is important to acknowledge its limitations and outline avenues for future research.

- *Simulation-Reality Gap*: The findings are based on a calibrated simulation model. While MassMotion's social force model is well-validated, it cannot perfectly capture the full spectrum of human behavior, such as panic or non-compliance. Future work should involve pilot implementations and post-optimization field measurements to validate these simulated results in a real-world setting.
- *Generalizability*: This research is an in-depth case study of a single, complex interchange station. The effectiveness of the specific structural and operational changes may vary for stations with different layouts, passenger compositions, or cultural contexts. Future research should apply this evaluation framework to a wider variety of station typologies to develop more generalizable design principles.
- *Static vs. Dynamic Optimization*: The proposed scenarios are static, pre-defined interventions. Modern transit management is increasingly moving towards real-time adaptive systems. Future research could explore integrating this simulation framework with real-time passenger flow data to develop dynamic control strategies, such as adaptive signage or responsive access control that can adjust to unexpected disruptions.

## 7 Conclusion

This study established a "simulation-optimization-evaluation" framework to assess the effectiveness and resilience of integrated congestion mitigation strategies for complex metro interchange stations. Applying this framework to the Liyuan South Road Station case study, we demonstrated that while multiple optimization scenarios can reduce peak-hour congestion, only an integrated approach combining both operational and structural measures provides the necessary resilience against significant future passenger growth. A systematic analysis of passenger flow dynamics during peak hours under a long-term operational scenario was conducted for this complex interchange hub. Three optimization strategies were proposed and evaluated: Scenario 1 (Operational Adjustment), focusing on optimizing existing facilities; Scenario 2 (Structural Modification), involving physical spatial layout alterations; and Scenario 3 (Integrated Optimization), which combines both operational and structural measures.

The results demonstrate that the integrated optimization scenario yields the most significant improvements. During the long-term morning peak, the station-wide average density decreased by 9.39%, and the maximum density was reduced by 2.31%. Moreover, the proportion of passengers experiencing severe LOS F congestion on Line 2 and Line 8 platforms decreased by 38.96% and 13.97%, respectively, resulting in substantial enhancements in both operational efficiency and safety. Notably, the integrated scenario also exhibited superior resilience under passenger flow stress tests: when simulated passenger volumes reached 1.7 times the long-term forecast, it maintained robust performance, whereas the original and other optimized scenarios exhibited severe congestion (average density exceeding 3.8 agents/m<sup>2</sup>) at lower stress levels (1.3–1.4 times). Under these extreme conditions, the integrated approach kept average densities within safe thresholds across eight identified congestion-prone points, clearly evidencing its enhanced safety margins and adaptability to projected passenger growth.

The application of simulation-based evaluation at Liyuan South Road Station demonstrates how integrated operational and structural strategies can improve passenger flow management in metro interchange stations, providing practical insights for similar contexts.

In conclusion, this research delivers practical optimization scenarios and robust data validation for Liyuan South Road Station, confirming the efficacy of integrated strategies. The methodologies and technical insights presented are broadly applicable to the planning, operational management,

and safety assurance of similar interchange hubs. Future work should focus on incorporating real-time data and refined operational controls, extending the approach to

diverse interchange station typologies, and further developing comprehensive theories and methodologies for passenger flow management and congestion risk mitigation.

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