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QUANTIFYING THE RESILIENCE CONTRIBUTION OF UNDERGROUND PEDESTRIAN SYSTEMS FOR SOLAR EXPOSURE RISK REDUCTION IN URBAN HEATWAVES

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Abstract: Urban heatwaves pose significant risks to pedestrian comfort and mobility. This study develops a simulation-based framework to evaluate the climate resilience performance of underground pedestrian systems (UPS) in mitigating solar exposure during extreme heat events. Integrating meteorological data, urban morphology, and pedestrian flows, the model employs multi-agent simulation and a spatiotemporal "path-risk" exposure framework to estimate the potential reduction in surface-level exposure enabled by UPS use. The method is applied to the Tenjin district in Fukuoka, Japan, where hourly UPS effectiveness is quantified under different climatic and demand conditions. A set of spatial resilience indicators is proposed to reveal dynamic patterns of risk avoidance, system contribution, and beneficiary distribution. Results show that resilience benefits are driven by both solar exposure intensity and pedestrian demand, with marked temporal variability and spatial heterogeneity. The findings highlight the role of UPS as a strategic climate adaptation infrastructure and provide a decision-support tool for resilience-informed urban planning and underground space design.

Keywords: Underground pedestrian system, Urban heatwave resilience, Solar exposure mitigation, Agent-based simulation, Spatiotemporal risk modeling.

1. INTRODUCTION

Urban heatwaves, as one of the most pervasive climate disturbances in recent years, have significantly altered the comfort of pedestrian microenvironments, indirectly affecting residents' travel behaviors and public health (Hess et al, 2023). During hot summer months, street environments exposed to direct solar radiation increase the risk associated with pedestrian activity (Basu et al, 2024, Melnikov et al, 2022, Azegami et al, 2023, Melnikov et al, 2017). High-temperature exposure reduces the comfort and safety of street-level walking environments, subsequently decreasing the willingness of residents to use public transportation such as subways and buses. This shift in travel behavior may lead to increased carbon emissions, thereby exacerbating urban heat island effects and contributing to global climate warming.

Underground pedestrian systems (UPS) play a vital role in mitigating the impact of urban heatwaves. Characterized by environmental stability, underground spaces provide effective protection against extreme weather. In recent years, UPSs in areas surrounding transit stations have developed towards networked, large-scale, and systematic configurations, allowing pedestrians to directly access services within the station domain (Gu et al, 2018). When surface-level pedestrian systems are impaired by high temperatures or adverse weather, networked UPSs offer alternative routes for regional pedestrian mobility (Cui and Lin, 2016, Zacharias and Wang, 2021). Moreover, pedestrian flow in UPSs contributes potential commercial vitality and social service value, further

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driving the development of such networks. As such, the planning of UPS has become an essential strategy for reconciling the conflict between urban travel demands and climate disturbances (Zacharias, 2000).

Practical cases in Sapporo, Montreal, and Singapore have demonstrated that connected underground pedestrian networks can effectively mitigate the impact of snow accumulation and solar exposure on transit passenger flows (Hess et al, 2023). However, there is a notable lack of systematic, quantitative assessments regarding the contribution of UPSs to the climate resilience of pedestrian systems. Establishing a measurable framework for evaluating UPS resilience performance is critical—not only to guide decisions in underground spatial development but also to provide a verification tool for urban designers and planners seeking to enhance the adaptive capacity of UPS networks.

Quantitative evaluation of UPS resilience presents several challenges. In the context of summer heat exposure, the efficacy of UPSs in reducing pedestrian exposure risk is influenced by a complex interplay of climatic conditions, street-level environmental factors, three-dimensional network structures, pedestrian demand, and behavioral decisions. As such, the response of UPSs to heat stress represents a complex systems problem. From the perspective of environmental risk, the urban thermal environment is shaped by variables such as temperature, humidity, wind speed, and solar radiation, all of which exhibit significant spatial and temporal heterogeneity. Consequently, heat exposure scenarios dynamically vary with time, date, and weather conditions. In terms of pedestrian behavior, the spatial and temporal distribution of underground pedestrian flows reflects distinct daily rhythms, causing the benefits of UPS interventions to shift over time. Additionally, individual perception of heat risks and corresponding path adjustments introduce further uncertainty into exposure outcomes. Thus, the mitigation capacity of UPSs cannot be accurately captured through static analyses of spatial pedestrian distribution and risk exposure.

To address these challenges, this study proposes a climate resilience performance evaluation model for UPSs based on spatiotemporal exposure simulation using a “path-risk” framework. Applying this model to the Tenjin district of Fukuoka, Japan, the study estimates the spatiotemporal distribution of solar exposure during summer and quantifies the contribution of the Tenjin UPS in reducing pedestrian sun exposure. Furthermore, spatial visualization metrics are established to reveal the dynamic distribution patterns of risk scenarios, beneficiary populations, and system response efficiency, thereby uncovering the mechanisms through which climatic conditions and travel demand affect the resilience performance of UPSs

2. METHODS

The basic framework of the model is shown in Figure 1. This model integrates multi-source inputs, including meteorological observations, urban morphology, and pedestrian flow data. It employs multi-agent simulation across various spatiotemporal scenarios to identify the spatial relationship between pedestrian routes and solar exposure risk. Based on the simulation results, the quantitative indicators are defined to evaluate the effectiveness of the UPS in mitigating high-temperature stress. Spatial visualization techniques are then applied to reveal the spatiotemporal dynamics of the systems’ resilience response.

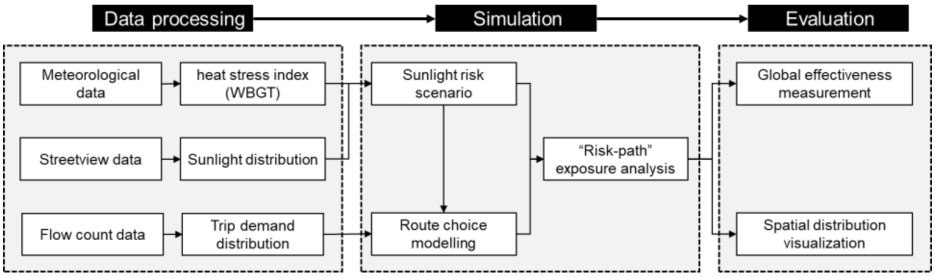
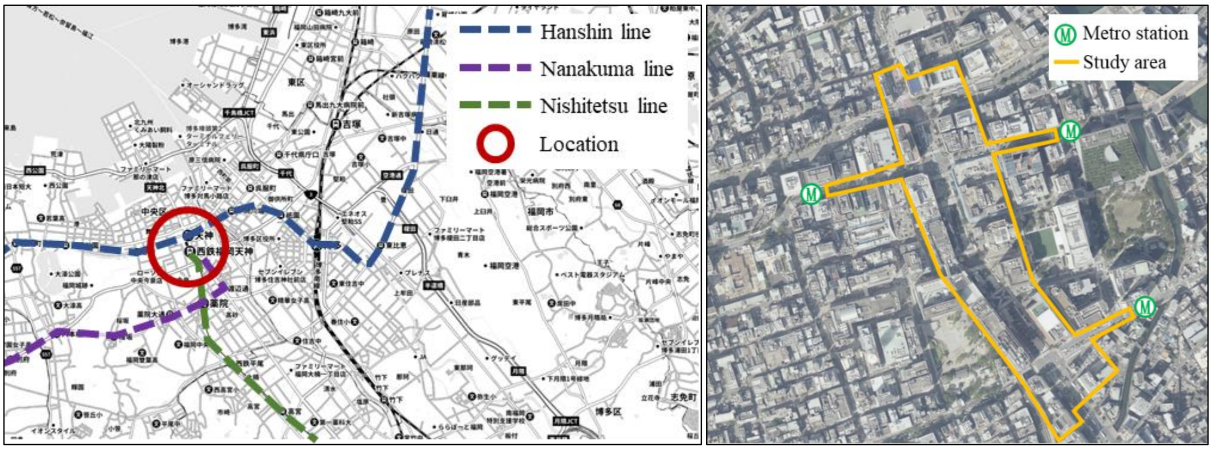


Figure 1. *Model framework.*

2.1. Study area and available data

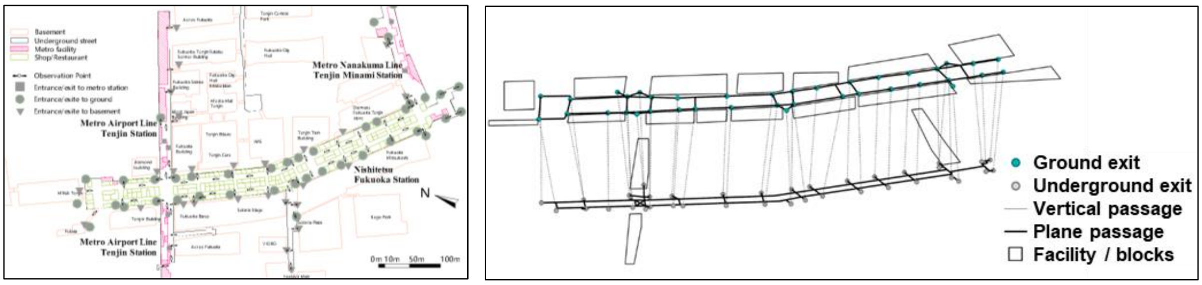
This study chooses the Tenjin district of Fukuoka City, Japan, as the case study location (Figure 2(a)) for the simulation experiment. Fukuoka City is located at 33 degrees north latitude and features a humid subtropical climate with hot summers and mild winters. According to historical meteorological data published by the Japan Meteorological Agency, the highest average monthly temperatures typically occur in August. To capture the temporal extent and representativeness of summer heat exposure, the simulation period is set from July 1st to September 30th.

This study selects the Tenjin underground shopping street and its surrounding connected urban blocks as the study area (Figure 2(b)). The underground shopping street features a linear spatial layout and maintains strong connectivity with adjacent land parcels and transit stations, as illustrated in Figure 3(a). Using open-access urban spatial information models, data on block morphology, building locations, and pedestrian pathways (both surface and underground) were extracted. Based on these data, a three-dimensional pedestrian network connecting facilities within the study area was constructed (Figure 3(b)).



(a) (b)

Figure 2. *Location and study area.*



(a) (b)

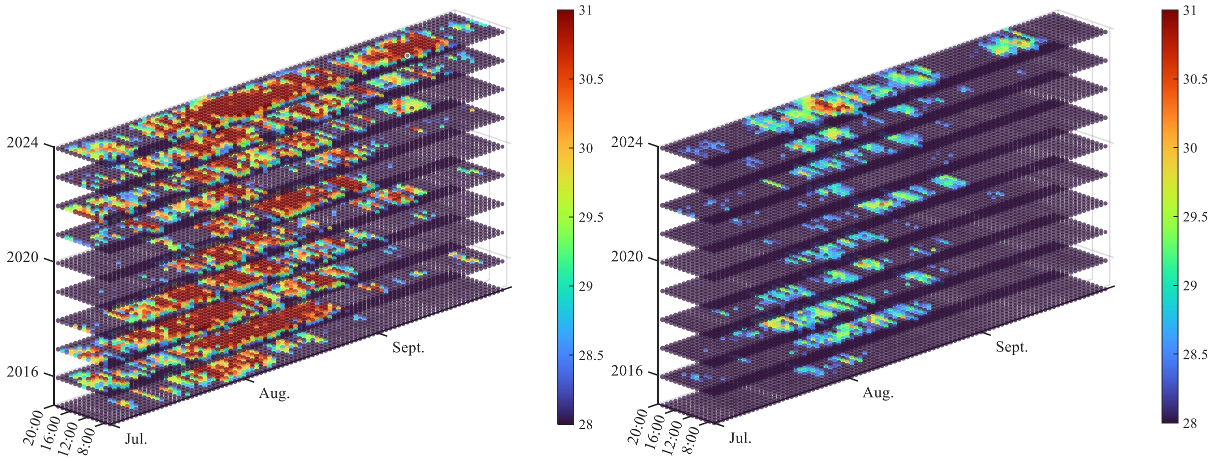
Figure 3. *3-dimensional pedestrian network modelling：(a) area of underground shopping streets; (b) connection between ground and underground pedestrian system.*

The model utilizes three primary data sources as input: meteorological observations, pedestrian flow counts, and streetview imagery. Meteorological data are derived from publicly available weather station records released by Japan's Ministry of the Environment (JME) and the Japan Meteorological Agency (JMA). These datasets include hourly recordings of temperature, humidity, weather conditions, wind speed, sunshine duration, and Wet-Bulb Globe Temperature (WBGT) index from 2015 to 2024. Pedestrian flow data are provided by the Fukuoka City goverment and consist of bidirectional pedestrian counts at major links of the Tenjin underground shopping street. This data recorded hourly from 7:00 to 20:00 on both weekdays and weekends. Streetview data were collected via the Google Street View API at 10-meter intervals along the street network, allowing for detailed analysis of shading conditions and visual environmental features.

2.2. Heat risk scenario identification

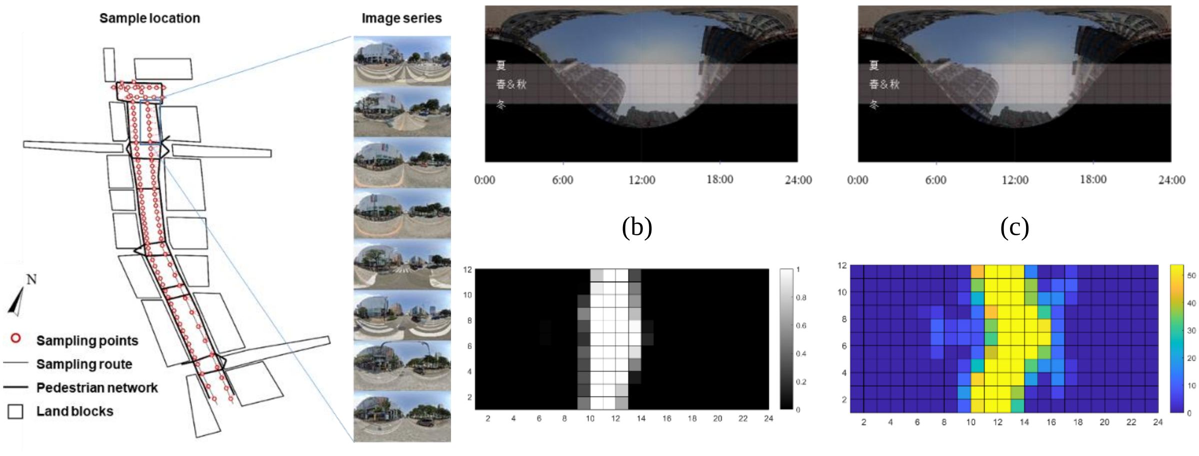
A heatwave is typically defined as a weather event during which the maximum daily temperature exceeds 35°C for three days. However, under direct solar radiation, pedestrians may experience equivalent thermal stress at significantly lower ambient temperatures (Hess et al, 2023). To more accurately define heatwave conditions, this study adopts the Wet Bulb Globe Temperature (WBGT) index, recommended by the Japan Ministry of the Environment(JME), as the key climatic parameter for heat risk assessment. According to the JME's heat alert policy, periods when the WBGT exceeds 31 (approximately equivalent to an air temperature of 35°C) are classified as "heatwave periods." In this study, street segments exposed to direct sunlight during these periods are defined as "solar exposure risk scenarios." The spatiotemporal distribution of such heatwave scenarios is therefore jointly determined by the timing of extreme heat and the spatial layout of exposed pedestrian facilities.

To assess whether the UPS can effectively support surface-level streets and mitigate heat exposure risks, this study is to check the WBGT indexs under shaded condition. Using weather station observations and the heat stress index framework provided by the JME and JMA, the WBGTs for each street link across time periods under both sunlit and shaded scenarios are estimated (Figure 4). It is found that the heat stress can be significantly mitigated if pedestrians move throung the underground paths without direct sunlight.



(a) (b)

Figure 4. *Time distribution of WBGT index in the past ten years: (a) WBGT in sunlight; (b) WBGT in shadow.*



(a) (b) (c) (d) (e)

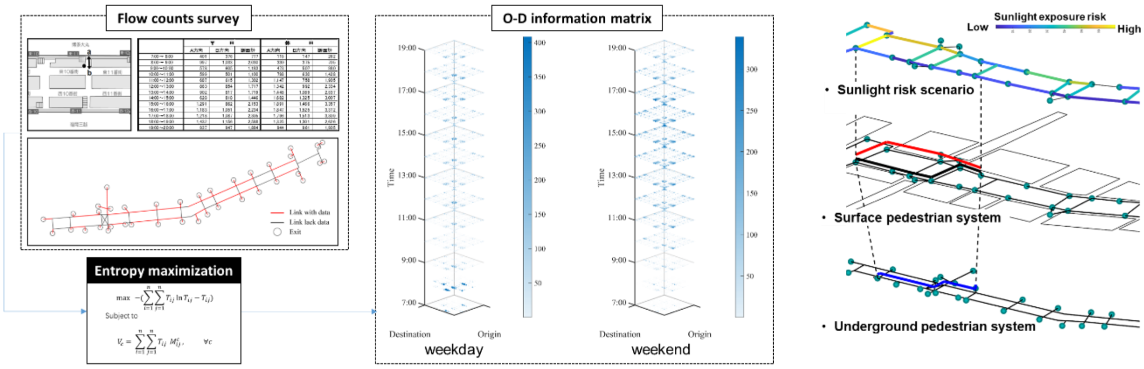
Figure 5. *Method of estimating sunlight scenario's spatiotemporal distribution in street networks: (a) streetview image sampling; (b) overlap solar trajectory; (c) projection transformation; (d) sunlight probability matrix; (d) sunlight route length.*

The spatiotemporal distribution of sun-exposed pedestrian links is determined by urban morphology, geographical orientation, and street-level environmental conditions. To capture the dynamics of sunlight risk across the pedestrian network, this study adopts a sequential street view image analysis approach (Zhu and Gu, 2022). As shown in Figure 5, by aggregating the temporal distribution of sunlit conditions at each sampling point (Figure 5(a)), we obtain time-series data on the sunlight and shaded lengths of each surface street. When integrated with WBGT indexs, a time series of sun-exposure risk across pedestrian paths is obtained.

2.3. Pedestrians' sunlight exposure estimation

The effectiveness of the UPS in mitigating solar exposure risk can be assessed by evaluating the additional exposure pedestrians would face if underground paths became inaccessible. This exposure level is influenced by pedestrian demand in the underground system, the spatial distribution of heatwave conditions above ground, and pedestrian route choice behavior under thermal stress.

Maximum Entropy model is adopted to estimate the trip demand that would be assigned to the surface network during UPS disruptions. Using observed flow data from underground passages, the module estimated the hourly origin-destination (O-D) matrix $\{T_{ij}\}_t$ for all entry-exit pairs.



(a) (b)

Figure 6. *Method of recreating pedestrians' trip demand and potential trajectories: (a) OD estimation module; (b) trip assignment in surface street networks.*

The Route Choice model considers pedestrian preference for shaded paths during extreme heat events. A utility-based function is constructed for each street link, incorporating factors such as route length, sun exposure length, intersection wait time, and vertical motion. The cost function is formulated as follows:

$$C_{lt}=d_l+\alpha_1 S_l+\alpha_2 W_1+\alpha_3 D_{lt} \quad (1)$$

The values of coefficients α_n are setting based on previous research. Detailed references and parameter settings are provided in Table 1.

Table 1. *Transition Efficient between pedestrian facility/environment factors and link distance.*

Parameters	Weighting	Unit transfer	Reference
Length (d_l)	1	-	Hiroyuki Satoh et al, 2002
Stair (S_l)	1.2(upwards) / 0.6(down)	meter/step	
Traffic signal (W_l)	30	meter/turn	Nishimura and Osaragi, 2009
Sunlight duration (D_{lt})	0.196/ 0.098 (tree shading)	meter/sec	Melnikov et al, 2022

To account for the influence of cloud cover and similar meteorological factors on sun exposure and pedestrian decision-making, this study classifies pedestrian route choice behavior into two categories: distance (or time) priority and utility-based priority.

During periods of significant cloud cover, which mitigates solar radiation, pedestrians are considered to adopt a distance-priority strategy, selecting the route with the shortest travel time (red line in Figure 6(b)). Conversely, under clear sky conditions with direct sunlight, pedestrians are expected to adopt a utility-priority strategy, choosing paths based on a trade-off between sun exposure and physical cost (black line in Figure 6(b)).

For each OD pair (i-j), both route types were generated by the Dijkstra algorithm under different solar exposure conditions. The proportion of pedestrian traffic along a surface-level road segment l at time t is determined by the following equation:

$$P_{ijlt}=Y_tL_{ijlt}+(1-Y_t)\,K_{ijlt}, \tag{2}$$

where P_{ijlt} denotes the proportion of trips from origin i to destination j traversing segment l at time t; Y_t is the normalized sunlight duration (range: 0–1) at time t; L_{ijlt} and K_{ijlt} are the frequencies with which link l is chosen under distance-priority and utility-priority decision-making.

By aggregating sun exposure durations across two types of route choices, the expected heat exposure risk for pedestrians between each OD pair is measured. Accordingly, the expected exposure reduction benefit provided by the UPS system for underground users is calculated as:

$$W_{ijt}=Y_tB_t\sum_l P_{ijlt}D_{lt} \tag{3}$$

where B_t is boolean indicator of WBGT > 31 (1 if true, 0 otherwise).

2.4. Performance indicator definition of UPS's resilience

Global Resilience Effectiveness: The total exposure reduction achieved by the UPS system at time t is calculated as the sum of expected exposure mitigation across all OD pairs:

$$F_t=\sum_i\sum_j T_{ijt}W_{ijt} \tag{4}$$

Risk Coverage Index：This index quantifies the contribution of UPS in reducing exposure risks on surface-level street networks, defined as the cumulative added exposure under the absence of the UPS:

$$R_{lt}=\sum_i\sum_j T_{ijt}P_{ijlt}D_{lt} \tag{5}$$

Resilience Benefit Index: Taken the street blocks and facilities as spatial unit, this index defines the cumulative risk avoidance of pedestrians between a specific O-D pairs as the spatial variation in exposure risk avoided by users, revealing the spatial distribution of benefit recipients:

$$G_{ijt}=T_{ijt}W_{ijt} \tag{6}$$

Resilience Contribution Efficiency Index: This indicator evaluates the efficiency distribution of the UPS network, assigning avoided exposure risk to each network component:

$$E_{kt}=\sum_i\sum_j G_{ijt}U_{ijkt} \tag{7}$$

where U_{ijkt} represents the frequency that OD path (i-j) traverses network element k (Gu and Osaragi, 2017).

3. RESULTS AND DISCUSSION

3.1. Results of system indicators

Figure 7 illustrates the relationship between the annual resilience effectiveness of the UPS system in mitigating pedestrian heat exposure and ambient temperature variations. Compared to daily maximum temperature, the consistency between the UPS performance and mean daytime temperature is notably stronger. While the effectiveness of the UPS system showed an increasing trend from 2021 to 2023, the overall contribution remained lower than in 2020, a year with lower average temperatures. This suggests that temperature alone is not the decisive factor driving the system's response.

To further explore the underlying causes of these variations, Figure 8 presents a temporal analysis of the UPS's exposure mitigation effectiveness across different dates and hours over the past decade. Although the total number of responsive days increased during 2021–2023, the effectiveness was fragmented due to frequent rainfall events, which interrupted continuous solar exposure and reduced UPS demand. In contrast, the reduced precipitation in 2024 resulted in prolonged clear-sky conditions**,** which significantly enhanced the UPS system's mitigation performance.

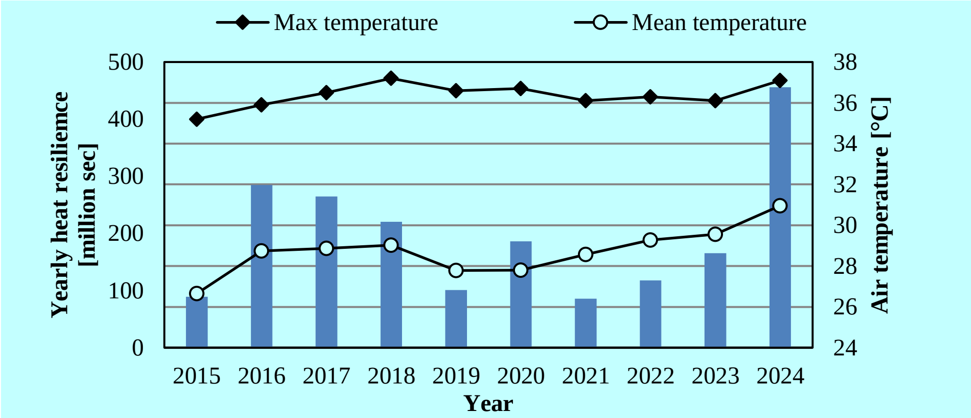


Figure 7. *Yearly variation of UPS's resilience effectiveness and air temperatures.*

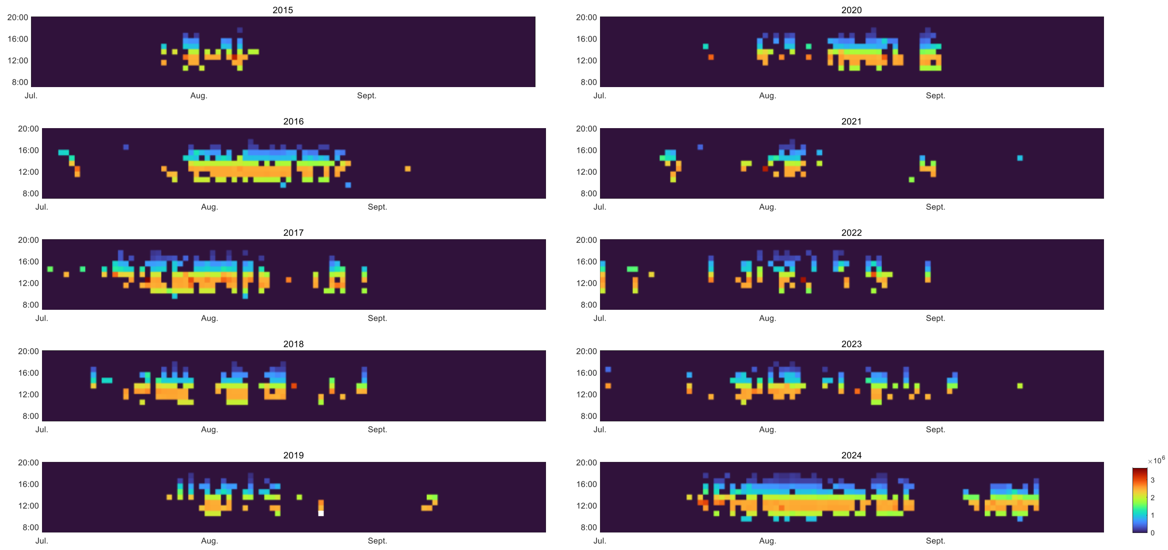


Figure 8. *Time-specific performance of UPS in mitigating pedestrians' sunlight exposure during the past 10 years.*

3.2. Spatial distribution of performance indicators

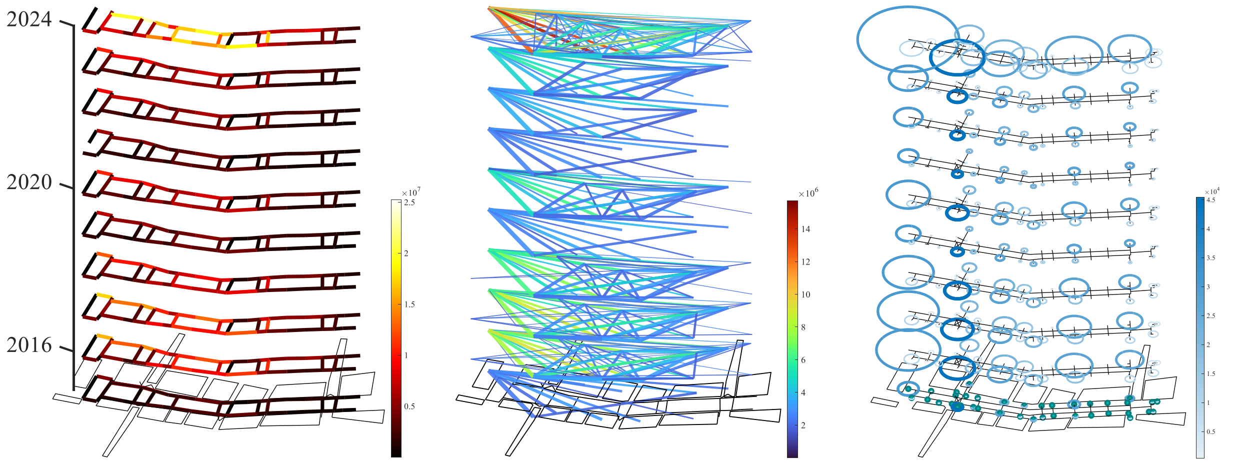
Figure 9 presents the spatiotemporal variation of three resilience contribution indicators (Risk Coverage Index, Resilience Benefit Index, and Contribution Efficiency Index) across different street elements over the past decade. Each layer in the figure illustrates the longitudinal change of these values from bottom (earlier years) to top (recent years). A strong alignment is observed between the temporal patterns of these indicators and the overall system effectiveness, revealing the UPS network's ability to globally respond to climate fluctuations.

In Figure 9(a), the spatial distribution of the Risk Coverage Index shows a significant north-south gradient, with higher values concentrated in the northeastern parts (left) of the study area. This is attributable to the greater pedestrian demand in the north. Besides that, the orientation of southern streets, which aligned east-west, making them more likely to be shaded by surrounding buildings and thus less prone to intense solar exposure (see Figure 2(b)).

Figure 9(b) visualizes the Resilience Benefit Index between O-D pairs. Line colors reflect the degree of solar exposure avoided due to UPS use, while line width indicates the volume of travelers along each O-D pair. The presence of long, wide paths with low benefit scores (cold-colored lines) suggests that travel volume and distance alone do not account for resilience gains**;** rather, trips' spatial relation between risk scenarios play critical roles.

In **Figure 9(c)**, the spatial distribution of Contribution Efficiency (represented by the radius of the circular plots) appears discontinuous. Interestingly, entrances directly connected to the surface show lower efficiency values than those integrated into commercial complexes. This is due to the convenient vertical circulation systems (e.g., escalators) within commercial facilities, which facilitate seamless movement between underground systems and surrounding amenities. The increasing the actual usage intensity leads to high contribution effeciency. Notably, the correlation between entry/exit traffic volume and contribution efficiency is strong,

In summary, the spatial variation of the UPS system's resilience effectiveness is highly heterogeneous, shaped by a combination of climatic dynamics, urban morphology, infrastructure layout, and mobility demand. These interactions cannot be adequately captured using single-variable linear models.



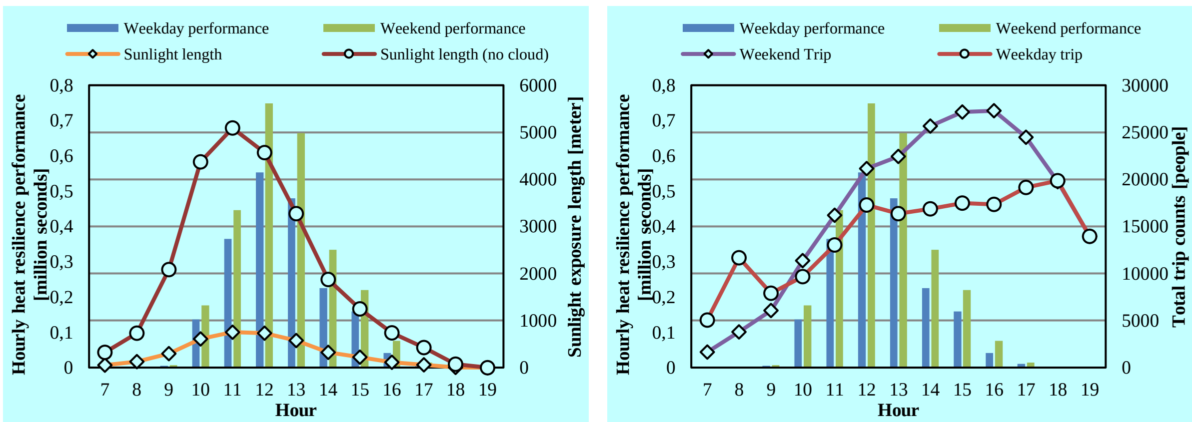
(a) (b) (c)

Figure 9. *Spatiotemporal distribution of resilience response performance indexes: (a) Risk Coverage Index;(b) Resilience Benefit Index;(c) Resilience Contribution Efficiency.*

3.3. Influence of underground trip demands on UPS's resilience contribution

This study selects 2024, the year with the highest solar exposure risk, to analyze hourly average global resilience effectiveness in the weekdays and the weekends. As shown in **Figure 10(a)**, the UPS system's mitigating effect becomes evident starting at 10:00 AM and dispeared after 4:00 PM. This pattern results from reduced solar exposure in early morning and late afternoon due to building shadows and lower solar altitude angles**.** Accordingly, the UPS's resilience effects during peak commuting hours are not activated.

The daily contribution index variation follows an approximately normal distribution which peaks around 12:00 PM**.** It is found that the peak lags behind the temporal peak of surface solar exposure (red curves in Figure 10(a)). This lag is thought to be caused by the increasing pedestrian flow during midday, which sustains high UPS effectiveness even after exposure levels begin to decline. Hence, UPS's global resilience contribution is determined by the coupled effect of trip demand and climate factors.



(a) (b)

Figure 10. *Influencing factors that cause differences in the contribution performance of UPS in the weekdays and weekends.*

A comparison between weekdays and weekends reveals that starting at 10:00 AM, the total number of underground travelers on weekends are higher than that of weekdays. It is thought to leading to consistently higher contribution index values throughout the day. However, after 12:00 PM, even as pedestrian volumes continue to grow, no corresponding rise in the UPS resilience effectiveness is observed. This suggests that the spatial extent of solar exposure plays a dominant influence on UPS resilience performance, rather than the effect of sheer traveler volume.

4. DISCUSSION

The proposed framework presents advances in assessing the climate resilience contribution of UPS. By incorporating solar exposure during walking and waiting phases into pedestrian routing decisions, the model mathematically described how users dynamically navigate in surface street networks. This allows for a more realistic estimation of the respective contributions of each network to overall system resilience under heat stress. Furthermore, the integration of agent-based simulation across multiple temporal and spatial scenarios enables the model to reflect the variability and uncertainty of urban pedestrian responses to environmental conditions. This dynamic structure captures the complex interplay between climate disturbances, built form, and pedestrian decision-making processes, which is essential for understanding resilience as a complex system outcome. In addition, the model jointly considers user-side travel demand and system-side service capacity, providing a comprehensive framework for resilience assessment across different spatial units and time periods. The spatial visualization of resilience indicators facilitates practical application in planning, allowing for evidence-based support in scenario evaluation, stakeholder responsibility allocation, and the optimization of underground spatial design. Overall, the framework not only quantifies the climate resilience benefits of UPS with improved behavioral reliability but also extends its utility to urban design and management contexts where spatial equity and adaptive performance are increasingly central concerns.

Despite the model's demonstrated contributions, several limitations should be acknowledged. At present, solar exposure is the sole environmental variable integrated into the routing decision process, while other relevant climatic factors, such as ambient temperature, wind conditions, and humidity, remain unaccounted for. Incorporating these elements in future work would enhance the model's reliability in representing pedestrian behavioral response to dynamic heat stress. Moreover, the current framework focuses exclusively on UPS users, thereby omitting pedestrians within the broader station area, whose exposure and routing decisions may also be shaped by underground accessibility. The assessment of resilience relies primarily on exposure duration as the outcome metric; future research should consider integrating comprehensive thermal indices, such as the PET and account for heterogeneous comfort preferences across user groups. Additionally, the representation of origins and destinations by entrance-exits may oversimplify actual movement patterns within large facilities, potentially underestimating the spatial granularity of beneficiary distributions.

5. CONCLUSION

To address the challenge of quantifying the climate resilience performance of UPS, this study presents a simulation-based model that evaluates UPS effectiveness in mitigating sun exposure in heat waves. The model integrates spatiotemporally heterogeneous variables, such as climate conditions, urban morphology, pedestrian demand, and street-level thermal environments, and uses scenario-based agent simulations to derive quantitative and spatially explicit resilience indicators. These reveal the dynamic complexity of multi-factor responses within three-dimensional pedestrian networks.

Key findings from the case study include:

- Spatiotemporal heterogeneity in pedestrian flows and sun-exposure risk significantly amplifies both the complexity and unpredictability of resilience responses.
- System efficacy depends on both pedestrian volume and exposure severity, with exposure levels playing a dominant role in temporal variability of resilience benefit.
- Trip demands disparities and temporal shifts (e.g., weekday vs. weekend) shape cumulative exposure and resilience effectiveness, highlighting time-dependent patterns in user benefit.
- UPS resilience potential cannot be inferred solely from surface heat stress indicators, spatial patterns of effectiveness depend strongly on the underground network structure and pedestrians' dynamic response.

Moving forward, the model will be extended using city-scale pedestrian trajectory data to examine response patterns across diverse climatic scenarios. This will support the development of a more comprehensive multi-hazard resilience framework, providing a robust basis for resilience-informed planning, policy formulation, and the adaptive design of underground pedestrian systems.

6. ACKNOWLEDGMENTS

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