Research Paper

Agent-based Simulation for Assisting the Design of Urban Public Square to Balance High and Low Density Condition

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Abstract

Public squares are essential for enhancing the quality of life for urban habitants, which offers a proper environment for multiple daily activities including leisure, entertainment, and dining. It is found that these spaces are significantly more crowded during weekends and holidays, and pedestrians are less during weekdays. The number pedestrians in these spaces fluctuates significantly over time. However, current design studies often focus on high or low density using scenarios and overlooking the balance between these patterns, which is not capable to comprehensively assist design.

This research employs agent-based simulation and a social force model to predict pedestrian dynamics in urban public squares. By simulating both high-density (holiday) and low-density (daily) situations, the self-organization behaviours that emerge under varying conditions is analysed. It is found that the inner corner of a square is liable be low-density, and the connections between the street and the square are prone to be high-density. For the square in the T-junction, a triangle region near the through street tend to have low-density, and there are high-density regions near the route between the end street and through street; For the square at the crossroads, there are four small regions that are relatively low-density. Furthermore, the size and distribution of overcrowded and vacant spaces correlate with the specific space. It can be suggested that effective design strategies can mitigate overcrowding and optimize the use of available space, by adapting to the spatial shape and taking consideration of both the high and low density using scenarios. This research leverages agent-based simulation for the quantitative analysis of using condition of urban squares with different locations and specific using scenarios. The design solutions can be derived by comprehensively analyse the using situation of pedestrians with varying amount and walking destinations. Taking advantages of this method, the urban public square design can be more accurate and objective.

Keywords

Design strategy; Urban public square; Agent-based model; Social force model; Quality of life

1. Introduction

The attractiveness of shopping, dining, entertainment and other functions in urban pedestrian spaces is increasing to pedestrians, and the situation of excessive pedestrian gathering has become more and more serious, which leads to a series of problems such as poor leisure activity experience and even personal safety (Li et al., 2020). Public squares play a role in gathering people and connecting different routes, which is an important node that the gathering of people and the usage of space need to carefully coped with. Currently, crowd management and guidance are the widely used methods to solve the problem of excessive pedestrian gatherings. However, access restrictions harm pedestrians' leisure experience, and the importance of passive urban design methods that guide pedestrians to avoid excessive gatherings is recognized.

The passive design methods are usually based on prediction and analysis (Helbing et al., 2005). Walking behaviour prediction models are capable of predicting the movement status of pedestrians and correspondingly analyse the walking space, which can be divided into macro models, including continuum models (He et al., 2023) and network models (Moustaid and Flötteröd, 2021), and micro models, including social force models (Helbing and Molnár, 1995), speed obstacle models (Takanashi, 2024), and discrete choice models (Robin et al., 2009). Microscopic models have higher accuracy in simulating pedestrian movements and are suitable for analysing walking conditions in spatial environments and predicting trajectories of small-scale pedestrians (Hoogendoorn et al., 2014; Duives et al., 2016). This study mainly focuses on predicting and analysing pedestrian walking behaviour in urban pedestrian spaces in a single urban square, and is mainly applied to propose relevant design strategies. Therefore, microscopic models fit this research better.

Dobler et al. (2021) found that the usage of urban public space can be categorised as using scenarios on weekdays and weekends. The performance of environmental elements on low-density and high-density are found to be extremely different (Li et al., 2024). However, existing researches mainly engages in the design solution for low-density (Khotbehsara et al., 2025) or high-density situations (Villani and Talamini, 2023). The balance of low-density and high-density situation is still not properly settled to improve the quality of life of people.

This study aims to use the agent-based framework to predict pedestrian density distribution in urban public squares in high and low density conditions based on social force concept. The model proposed in this study can be used to assist in proposing design strategies accordingly. The pedestrian density distributions in different prototypes of urban public squares under normal and crowded conditions is considered simultaneously to balance both conditions to propose proper design solutions.

This paper first provides the research methodology to simulate the pedestrian density distribution. Accordingly, the results of the prediction results are subsequently described. Then, the application prospects are discussed. Finally, several conclusions are presented.

2. Methodology

The influencing factors shaping basic forms of urban public squares can be divided into straight and turning corridors, which determines direct and turning behaviours in the tactic layer. The model proposed in this study is a 2-layer agent-based model. The tactic model is a path planning model that predicts the current walking aim and gradually leads to the destination; The operational level is based on the walking aim predicted in the tactic layer model to perform instant walking behaviour. The pedestrian density distribution can be predicted through simulating walking behaviour of pedestrian crowds in the agent-based model. After the above steps, the relationship between influencing factors and pedestrian density distribution can be built, as shown in Fig. 1.

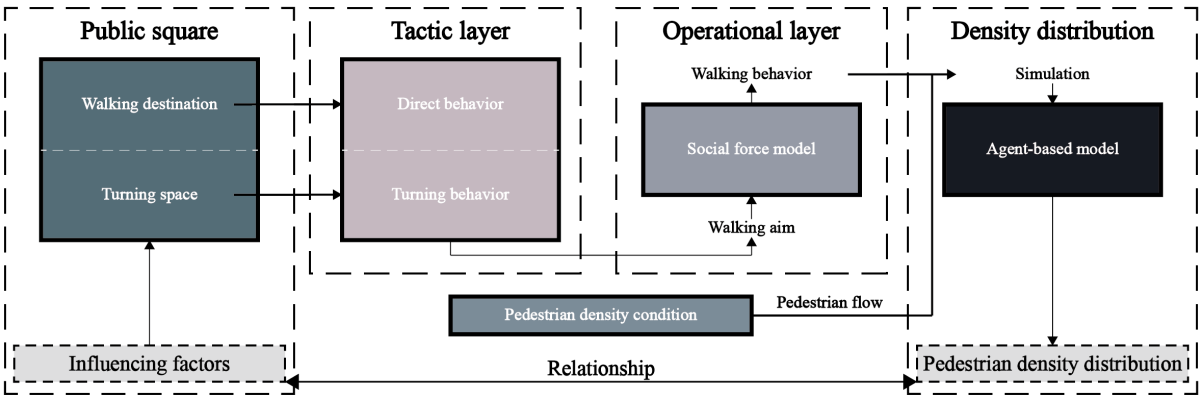

Figure 1 The logic of walking behaviour model. Source: Authors.

2.1. Tactic layer model

The influencing factors causes two kinds of tactic layer behaviours, which are direct behaviour and turning behaviour, as shown in Fig. 2. Based on the needs of reaching the target, the walking aims of pedestrians are determined by direct behaviour and turning behaviour.

- Direct behaviour

When pedestrians and their walking aims are in the same corridor, they will adopt the direct behaviour in the urban public square (Hoogendoorn and Bovy, 2005). Influenced be direct behaviour, pedestrians will cross the entire space with the shortest path, which means that the pedestrian's path planning at this time is a straight line towards the destination, with the expected direction directly pointing from the current position to the destination, reflecting the behaviour of approaching the destination. The walking aim of pedestrians' direct behaviour remains stable throughout the walking process, as shown in Figure 2.

- Turning behaviour

This study divides the turning behaviour of pedestrians under the influence of changes in the direction of the passage into three phases, namely the straight stage before turning (Phase 1), the passing turning region stage (Phase 2), and the straight stage after turning (Phase 3), as shown in Fig. 2 (Sun et al., 2023). The first phase is the straight stage before turning. In this phase, the pedestrian's tactic layer walking strategy is to go straight parallel to the boundary of the channel. The second phase starts at a distance of x_p upstream of the connecting region of the two corridors, and uses an elliptically global path planning method. The local path planning strategy is set an attentional scope with a radius of r. The connecting point in the walking direction is the walking aim in this phase. x_p is a random number with a mean of 5.82 m and a standard deviation of 2.4 m, and r is 3 m. The third phase is the straight stage after turning. In this phase, pedestrians will shift to direct behaviour.

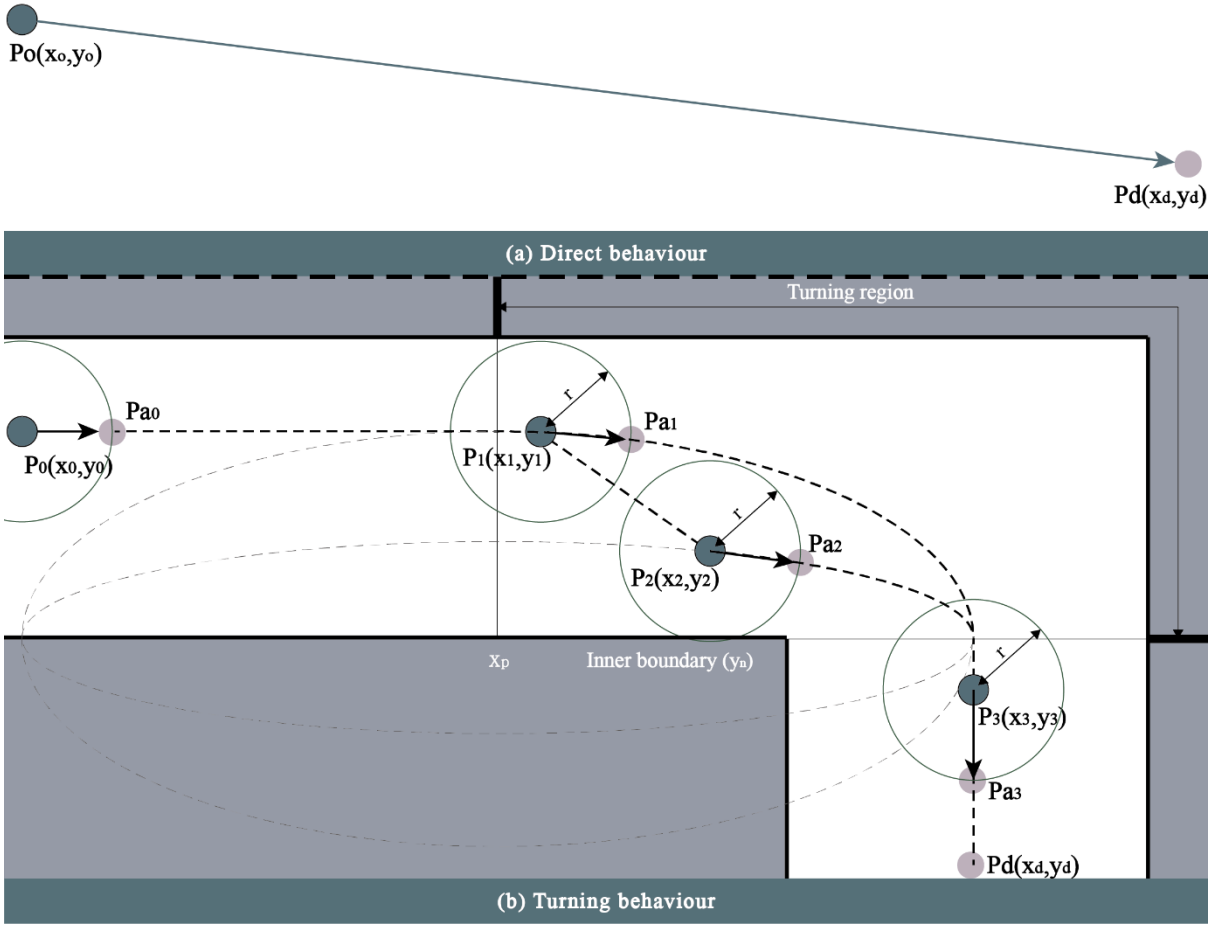

Figure 2 Walking aim setting of different tactic layer behaviours. Source: Authors.

2.2. Operational layer model

The social force model treats the influence on pedestrian movement as the form of force, predicting the acceleration of pedestrians after being affected by other influential factors. In the social force model proposed by Helbing et al. (2000), the pedestrian's motion acceleration (a) is influenced by expected walking vectors, physical boundaries, and other surrounding pedestrians. These effects on pedestrian movement can be understood as the forces acting on pedestrians from these three effects. If the influence from the expected walking vector is $\vec{f}_i^{\,0}$, the influence from the physical boundary is $\vec{f}_i^{\,wall}$, and the influence from a single surrounding pedestrian (j) is $\vec{f}_{ij}$, the calculation method for pedestrian acceleration (a) is shown in Eq. 1.

$$a = \vec{f}_i^{\,0} + \vec{f}_i^{\,wall} + \sum_j \vec{f}_{ij} \tag{1}$$

3. Result

Pedestrian squares are liable to exist at the intersection of streets. The urban pedestrian square at the intersection of streets can be divided into two spatial forms: the square at the T-shaped intersection and the square at the cross intersection. According to the importance of the cross axis in the region, these two spatial forms can be further divided into the intersection of the main axis and the secondary axis, and the intersection of the main axis and the main axis. The simulation includes a normal condition (low pedestrian flow) and a crowded condition (high pedestrian flow).

3.1. Pedestrian space at T-shaped intersection square

According to the axis level of the T-shaped intersection node, the pedestrian space of the T-shaped intersection square is divided into the interacting of the main street and the secondary street, and the interacting of main street and main street.

The using scenario of main street and secondary street is shown in Fig. 3. It can be found that the density of inner corners of the square are quite low. In addition, there is still a large area in the middle and near the through street that shows a low pedestrian density. For high-density regions, it can be noticed that the area near the end road can be extremely crowded, and the route connecting the end road and the through road can also be quite crowded in holiday and week (crowded) condition.

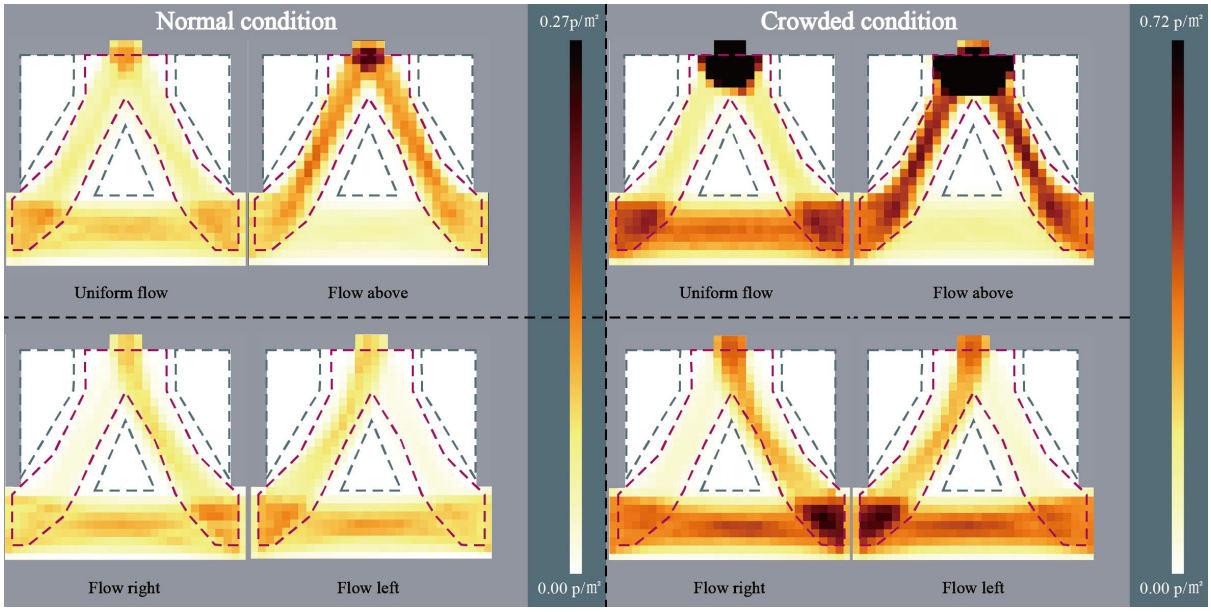

Figure 3 Prediction result of pedestrian space at T-shaped interaction square of the main street and the secondary street. The area enclosed by the green dashed line is low-density region, and the area enclosed by the red dashed line is high-density region. Source: Authors.

The using scenario of main street and main street is shown in Fig. 4. Comparing with the main street and main street condition, it can be found that the low-density region in the middle is apparently smaller, and extremely crowded area moves from the region near the end street to the region near the through road.

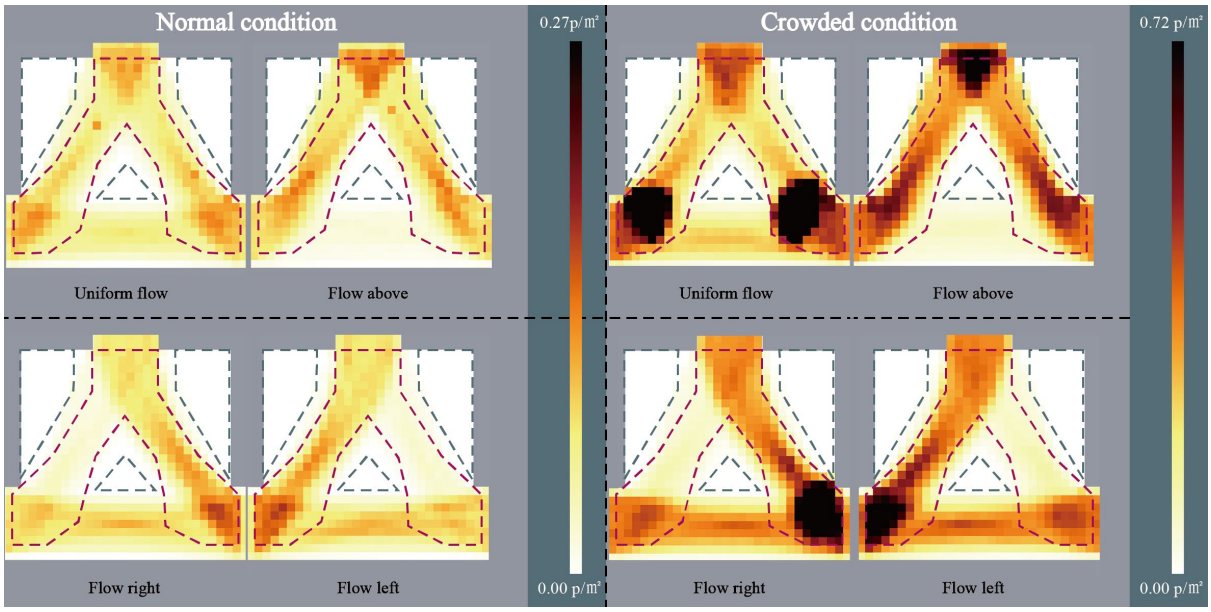

Figure 4 Prediction result of pedestrian space at T-shaped interaction square of the main street and the main street. The area enclosed by the green dashed line is low-density region, and the area enclosed by the red dashed line is high-density region. Source: Authors.

3.2. Pedestrian space at cross intersection square

According to the axis level of the cross intersection node, the pedestrian space of the cross intersection square is divided into the interacting of the main street and the secondary street, and the interacting of main street and main street.

The using scenario of main street and secondary street is shown in Fig. 5. It can be found that the density of all the four inner corners of the square are quite low. In addition, there are also four small elliptical regions around the central part show low-density. For high-density regions, it can be noticed that the area near the end road can be extremely crowded, and other regions are not easy to be over-crowded.

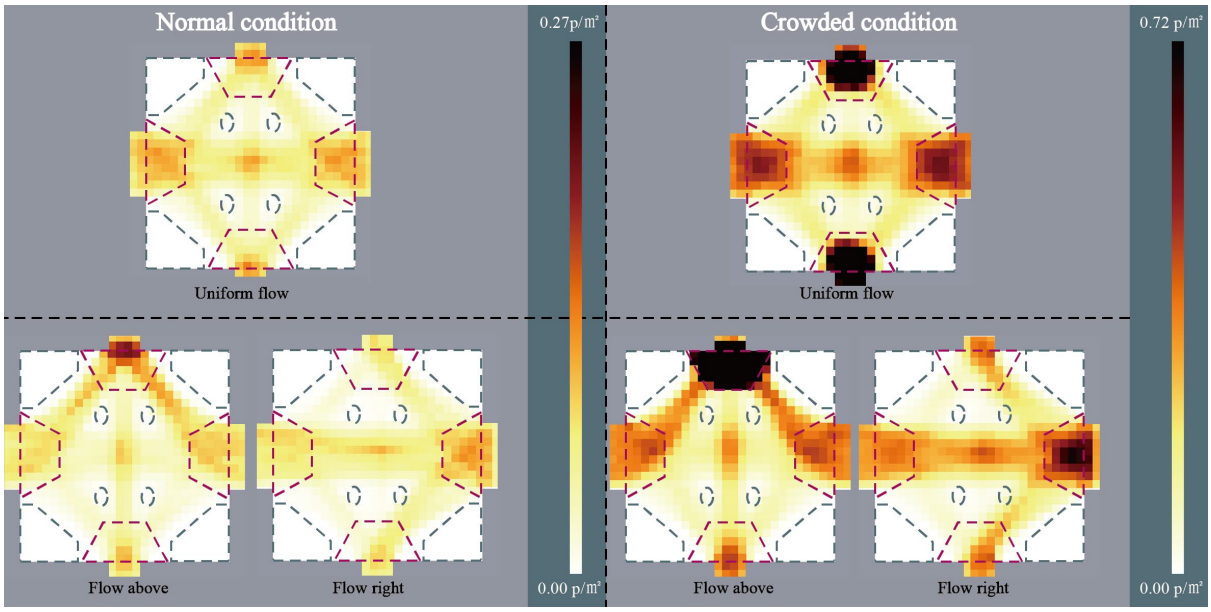

Figure 5 Prediction result of pedestrian space at cross interaction square of the main street and the secondary street. The area enclosed by the green dashed line is low-density region, and the area enclosed by the red dashed line is high-density region. Source: Authors.

The using scenario of main street and main street is shown in Fig. 6. Comparing with the main street and main street condition, it can be found that the low-density region in the middle is more like a circle, and extremely crowded areas are much larger.

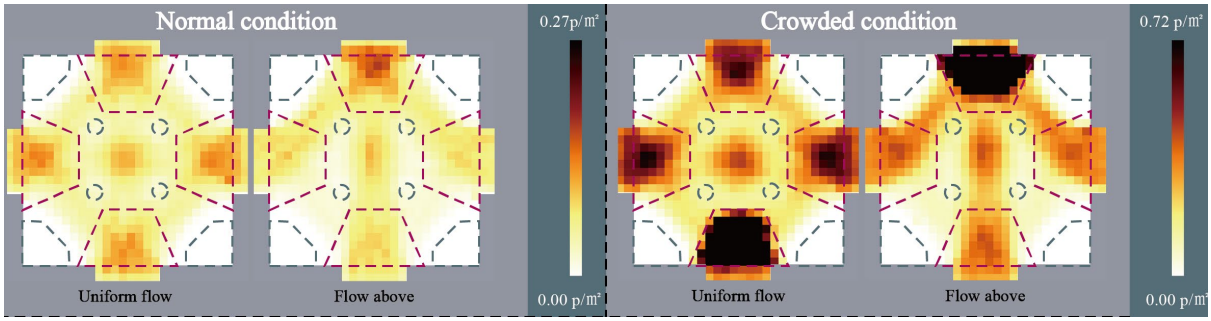

Figure 6 Prediction result of pedestrian space at cross interaction square of the main street and the main street. The area enclosed by the green dashed line is low-density region, and the area enclosed by the red dashed line is high-density region. Source: Authors.

4. Discussion

A couple of elements should be set up in a pleasant location for pedestrian environment. Based on the prediction results of pedestrian density distribution, design strategies for pedestrian space can be proposed accordingly.

For high-density regions, it can be noticed that they are prone to gather near the connecting of streets and squares. In some cases, the crowded areas can be dangerous if pedestrians continue to accumulate. There are still low-density regions exists. Low-density can be used to design activities according to their positions. For the area of inner corners, pedestrians can sit and rest here, and for the area near the central space of

the square, pedestrians will not want to stay there. In this kind of space, elements, such as street lights and trees can be designed there.

This study identified vacant areas and crowded areas of urban squares in both daily and holiday conditions, taking consideration of all kinds of pedestrian flow scenarios. Understanding the using scenarios of pedestrian in advance. Designer can make plans and avoid inappropriate spaces before the square is really built and propose a design strategy to fully utilize the pedestrian space in the square.

5. Conclusion

The pedestrian space in the square can significantly improve the comfort of pedestrians. This study has used a two-layer agent-based model to simulate the pedestrian density distribution in both daily and holiday conditions, which can assist in the design of urban squares.

Firstly, the overall trend of pedestrian density distribution in daily use (normal) and holiday use (crowded) is roughly the same. However, for some forms of pedestrian squares, there are certain differences in scope between the two, which should be treated with caution in design.

Secondly, the intersection space between streets and squares is particularly prone to pedestrian overcrowding, especially when the direction of pedestrian flow is a branch road. The pedestrian density at the junction of the branch road and the square will be very high. In addition, there will also be pedestrian overcrowding between the end road of T-junction and through street.

Thirdly, there may be local low-density areas in the interior corners of pedestrian squares and near the centre of the square. The low-density area in the centre generally deviates from the geometric centre of the square, and the specific location of the low-density area may vary depending on the form of the square. When applying low-density areas, they should be closely combined with the specific situation of the square to avoid the design results being counterproductive.

6. References

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