LAYOUT EVALUATION AND OPTIMIZATION STRATEGY FOR RETAIL SPACE INTEGRATION INTO EXISTING SUBWAY STATIONS: AN AGENT-BASED MODELLING APPROACH

A Case Study of Beijing Subway Line 4 Xiyuan Station

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Abstract. The sustained operational losses in rail transit, including subway systems, present a significant challenge for many major cities today. The question of how to generate revenue for subways has consistently been a prominent topic for architectural layout design and management. However, due to concerns about potential congestion and uncertain commercial potential, there has been persistent scepticism regarding the practice of incorporating retail spaces into existing subway stations to enhance non-ticket revenue. This study employed an Agent-Based Modelling approach using the MassMotion software to establish a framework that evaluates and optimizes the layout of retail spaces in existing subway stations based on density and visual analysis. The proposed methodology and digital approach would inform architects and decision-makers about optimized retail layout and spot allocation options that are beneficial for creating commercial value and alleviating congestion.

Keywords. Subway Station, Commercial Space Optimization, Agent-Based Modelling (ABM), Space Layout.

1. Introduction

Revenue from urban rail transit comprises ticket and non-ticket sources. Tickets are the main income for most companies, while non-ticket includes advertising and station commercial space rental. With China's urbanization, there are over 10,000 km of operating subway lines across 55 cities as of 2022 (CAMET, 2023). Beijing's subway, with 27 lines and 475 stations, sees high ridership but operates at a loss, accumulating over 500 billion CNY in debt as of May 2023 (Fang & Ran, 2023). Relying solely on advertising for non-ticket revenue is evidently a significant factor contributing to the subway's inability to generate profits. For the economic sustainability of the subway

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system, further research directed at enhancing non-ticket revenue is needed.

The potential for developing subway retail is enormous, but it also faces numerous challenges, including overcrowding and hygiene issues. Renovating subway stations poses challenges like geological, structural, and utility complexities (Garavito-Bruhn et al., 2012). As a result, using temporary structures or lightweight partitioning within existing spaces is an economically viable option. It is crucial to focus on crowd control and the visual aspects of shopping behaviour (i.e., visual guidance towards retail locations). Simultaneously, service types and spatial scales should also be considered.

This paper introduces a digital spatial optimization strategy incorporating pedestrian analysis, integrating visual (commercial value) analysis (Huang et al., 2018) and density (flowline organization) analysis using Oasys MassMotion. It innovatively combines spatial layout, visitor traffic, and crowding optimization within a single framework, establishing a universal assessment and optimization process for existing subway stations to guide revenue generation and congestion alleviation. In the long term, it will significantly impact rail system business model transformation, promoting economically sustainable public transportation development.

The article consists of seven sections. Starting from the third section, we provide detailed description of the methodology and research process, culminating in the presentation of visual results. Our conclusion indicates that the proposed method and framework effectively provide decision support and optimization recommendations for the retail space layout in existing subway stations. Moreover, they are applicable to other large public spaces such as airports and train stations.

2. Literature Review

The current research in subway transportation spans urban planning, design, land development, crowd behaviour analysis, commercial analysis, and operational management. In the commercial analysis of enclosed spaces like subways, airports, and bus stations, analysing pedestrian flow, and corresponding behaviour is crucial. Agent based modelling (ABM) can simulate complex real-world systems while considering interactions among individual agents, quantify and visualize outcomes (Stieler et al., 2022). The ability of ABM to model complex systems suggests there is potential for its application in decision-making and optimizing subway commercial space layout.

In the realm of behavioural analysis in railway transit stations, ABM has long been used to research the daily flow and emergency evacuation of subway passengers (Ma et al., 2017). The use of ABM based on "Cityflow" has revealed intricate pedestrian behaviour within subway stations (Wang et al., 2015). Similarly, ABM based on "Pathfinder" can be employed to summarize the behavioural characteristics of crowds during evacuations in subway stations (Wu et al., 2022).

Research on the relationship between subway and commercial (retail) space also has a lengthy history, indicating a positive correlation between rail transit development and the growth of surrounding businesses. Enhanced commercial viability and the expansion of employment opportunities in the vicinity are always linked to the growth of transit stations in California (Schuetz, 2015). The success of the commercial model of Tokyo Metro in Japan also indicates the positive role of retail spaces in increasing passenger traffic and commercial vibrancy (Zhang, 2018).

In economic analysis, both 2D and 3D visual graphic analysis (VGA) methods, including Space Syntax, IsoVist, and ABM, are widely used to assess the commercial vitality of specific spaces. The IsoVist method based on visual spatial features can be utilized for quantitative analysis of commercial pedestrian streets (Sun et al., 2023). Visual maps are also considered effective for reference in measuring design decisions and congestion impacts (Morrow et al., 2014). MassMotion has been used for studying the relationship between visual and commercial aspects in airports (Ma et al., 2020).

While these studies offer innovative insights, they often overlook spatial design exploration, especially in optimizing commercial layouts and addressing congestion. In contrast, our proposed framework subdivides "optimization" into three aspects: spatial layout, crowding, and visibility (consumption potential) optimization. The aim is to leverage high passenger flow to enhance retail profitability while alleviating congestion. With further case studies, this framework holds promise as a universally applicable retail layout paradigm for diverse public transit spaces.

3. Methodology

3.1. FRAMEWORK OVERVIEW

Figure 1 illustrates the workflow framework employed in this study. At its core, the framework involves continuous evaluation, analysis, and modification of the model through MassMotion, with iterative comparisons to achieve improved layout solutions.

This study aims to optimize the spatial layout, crowding, and visibility of subway stations. Spatial layout optimization includes general evaluation and magnification optimization. It identifies underutilized areas with good visibility and iteratively adjusts layouts based on simulation results. Crowding optimization reorganizes peak-hour pedestrian flow through retail spaces. Visibility optimization provides data for commercial potential of retail spaces through quantified analysis of simulated images, guiding designers toward consumer-oriented development.

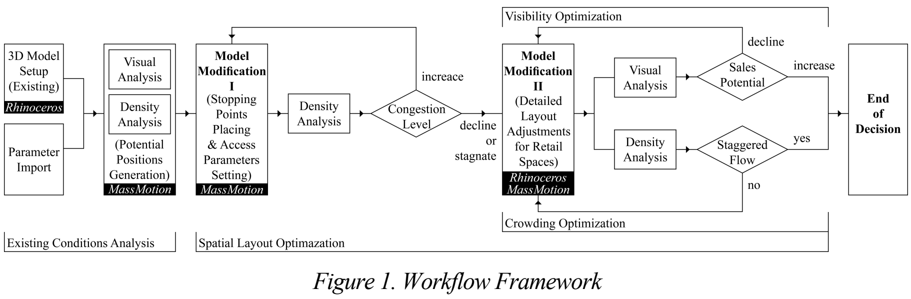

Figure 1. Workflow Framework

3.2. PARAMETERS

This study set up a simulation using on-site data, covering train arrivals intervals, passengers' waiting times, paths selection probabilities, and entrance/exit passenger flow. Retail-related parameters were gathered through off-site survey, including store dimensions, average visit durations, average service personnel limits, and passengers retail categories preference.

3.3. ANALYSIS

3.3.1. Principle of Density Analysis

In this study, we utilized "Experienced Density Maps" and "Maximum Density Maps" generated through MassMotion simulations as reference points. "Experienced Density Maps" illustrate the mean density encountered by agents (averaging all experiences) in the vicinity of each point, calculated through a weighted average (MassMotion Software, 2022). The measure is calculated as:

$$LOS(t) = \frac{\sum_{n=1}^{t} d\,ensity(n)^2}{\sum_{n=1}^{t} d\,ensity(n)}$$

In this context, "n" denotes the simulation frame number (e.g., frame 1, frame 2, frame 3, etc.), while "t" signifies the total number of simulation frames.

Experienced Density Analysis is sufficient to reveal the general trends in passenger movement pathways, potentially enabling the discovery of untapped valuable spaces; "Maximum Density Maps" depict the highest density achieved at each point within the specified time span (MassMotion Software, 2022).

3.3.2. Principle of Visual Analysis

As agents move, they project a forward-pointing cone of vision, marking the voxels within this cone as visible. The default cone has a 30-degree field of view and a 20-meter cutoff viewing range (MassMotion Software, 2022).

"Vision Count Maps" showcase the number of agents observing a specific point on an object, while "Vision Time Maps" reveal the accumulated time agents spend observing an object (MassMotion Software, 2022).

4. Case Study: Beijing Subway Line 4 Xiyuan Station

4.1. CASE INTRODUCTION

This paper examines Xiyuan Station on Beijing Subway Line 4. Despite being newly constructed, the station has a standard layout and faces high passenger traffic but lacks retail services. With five entrances, including one linking to Line 16, it features a hall and platform. Currently, there are no non-ticket-related commercial spaces within the station. The simulation study in this paper is limited to public areas used by passengers, which include the concourse, platform, restrooms, elevators, stairs, and escalators (as shown in Figure 2).

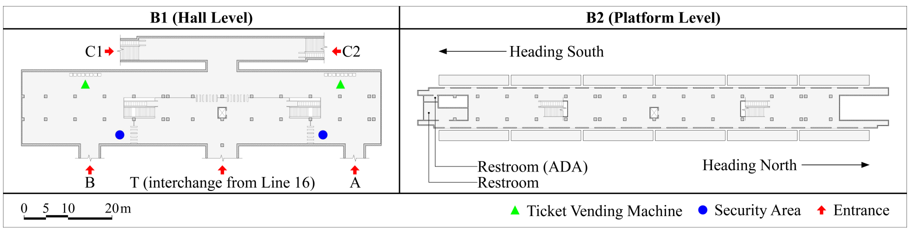

Figure 2. Station Layout Overview

4.2. DATA COLLECTION

Passenger flow data for Xiyuan Station was collected on November 20, 2023, as depicted in Figure 3. The data collection involved seven groups of participants. Five groups recorded video footage of the entrances, while two groups focused on the platform. Recording started at 7:00 AM on Monday, during peak hours, and lasted for one hour. We meticulously counted individuals entering the videos and estimated crowd movement direction based on observations to obtain the passenger flow data.

Field Study Snapshot

Entrance	Departures (persons)		4165	Arrivals (persons)		2568
	North	South	Subtotal	North	South	Subtotal
A	234	590	824	338	101	439
B	24	60	84	57	17	74
C1	194	489	683	498	149	647
C2	157	397	554	210	63	273
T	574	1446	2020	874	261	1135

Figure 3. Passenger Flow During Peak Hours: One-Hour Record

5. Simulation

5.1. PARAMETER SETTING AND IMPORTATION

Table 1 shows the parameters of newly added retail units including "Duration" (time for a purchase), "Capacity" (maximum customers accommodated simultaneously), and "Authority" (openness to the public). To mitigate passenger behaviour challenges, such as density, orientational dependence, and memory effects (Lakoba et al., 2005), pop-up stores and regularly updated retail spaces were integrated into the simulation.

	Small(S)	Medium(M)	Large(L)	Pop-up(P)
Duration	25s-45s	25s-45s	25s-120s	25s-300s
Dimension	3m x 3m	3m x 5m	3m x 6m	6m x 12m
Capacity	<=2	<=3	<=4	<= 20
Authority	staff only	staff only	staff only	public

Table 1. Parameters of Retail Units

Table 2 presents the physical parameters employed by agents within the simulation framework. These parameters are sourced from LUL Non-PRM (MassMotion Software, 2022), which is predominantly informed by the station modelling guide developed specifically for Transportation for London (TfL). The extensive sample size and comprehensive research background underpin its universality and authority.

	Basic		Route Cost Weights (Uniform)			
	Radius(m)	Speed(m/s)	Horizontal	Vertical	Queue	Processing
Min	0.12	1.1	0.75	0.75	0.75	0.75
Max	0.22	1.9	1.25	1.25	1.25	1.25
Mean	0.17	1.53	-	-	-	-

Table 2. Physical Parameters of Agent

5.2. GENERAL LEGENDS

Figure 4 shows the legends of the 4 different maps involved in the simulated results of this study. "Experienced Density" primarily emphasizes the average density during the simulation time, while "Maximum Density" represents the instantaneous maximum density. Therefore, there can be differences in the results illustrated in these maps.

	Experienced Density (agent/sm)	Maximum Density (agent/sm)	Vision Count (times)	Vision Time
	-∞ - 0	-∞ - 0	-∞ - 0	-∞ - 00:00:00
	0 - 0.31	0 - 0.31	0 - 1500	00:00:00 - 00:20:00
	0.31 - 0.43	0.31 - 0.43	1500 - 3000	00:20:00 - 00:30:00
	0.43 - 0.72	0.43 - 0.72	3000 - 4500	00:20:00 - 00:40:00
	0.72 - 1.08	0.72 - 1.08	4500 - 6000	00:40:00 - 00:50:00
	1.08 - 2.17	1.08 - 2.17	6000 - 7500	00:50:00 - 01:00:00
	2.17 - +∞	2.17 - +∞	7500 - +∞	01:00:00 - +∞

Figure 4. Legends (Value Range) for Maps

6. Results

6.1. EXISTING CONDITION EVALUATION: POTENTIAL POSITIONS

This part focuses on simulating the current conditions within the station to identify underutilized areas with high commercial potential. The Experienced Density Map highlights passenger pathways, with black areas indicating low visitation rates. By overlaying this map with the Vision Maps, we can pinpoint positions with optimal visibility and traffic flow. Given the smaller area of B2, we included its blue regions in the analysis of area exhibiting low visitation rates. Ultimately, we determined a total of four potential retail space locations based on the areas of greatest overlap (as depicted by the shaded regions in Figure 5).

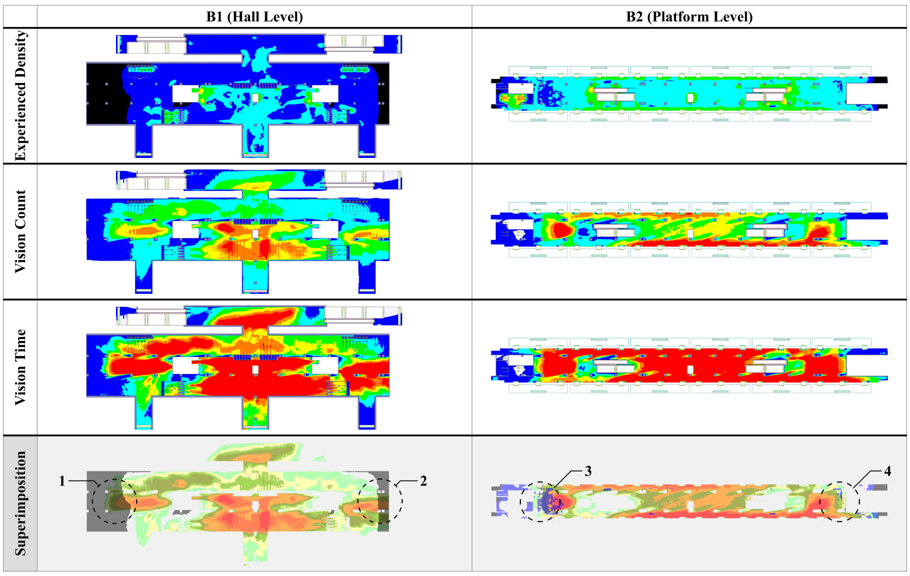

Figure 5. Potential Positions for Retail Units

6.2. OPTIMIAZATION I: STOPPING POINTS

In this section, we validate the effectiveness of the speculated locations in Section 5.1, specifically by employing Maximum Density maps to study the impact of passenger stops on potential locations and the resulting congestion. With a cautious approach towards platform areas, we conducted separate simulations to investigate the inclusion of stopping points on the platform. The primary research method in this section involved concentrating a certain number of "servers" within the target area to observe overall changes. Figure 6 illustrates the data obtained by quantifying each image (3840 x 2160) through histogram information, where pixel points with an error of <3% were considered.

The comparison reveals that the addition of stopping points (locations where agents will visit and pause for a moment) on B1 level will transform some previously unused (black) areas into yellow, green, and blue regions, without causing extensive additional red and orange areas. This allows us to conclude the effectiveness of positions 1 (P1) and 2 (P2). The comparison of B2 maps shows that adding stopping points at both ends of the platform effectively reduces the area of red and orange regions, validating the effectiveness of positions 3 (P3) and 4 (P4).

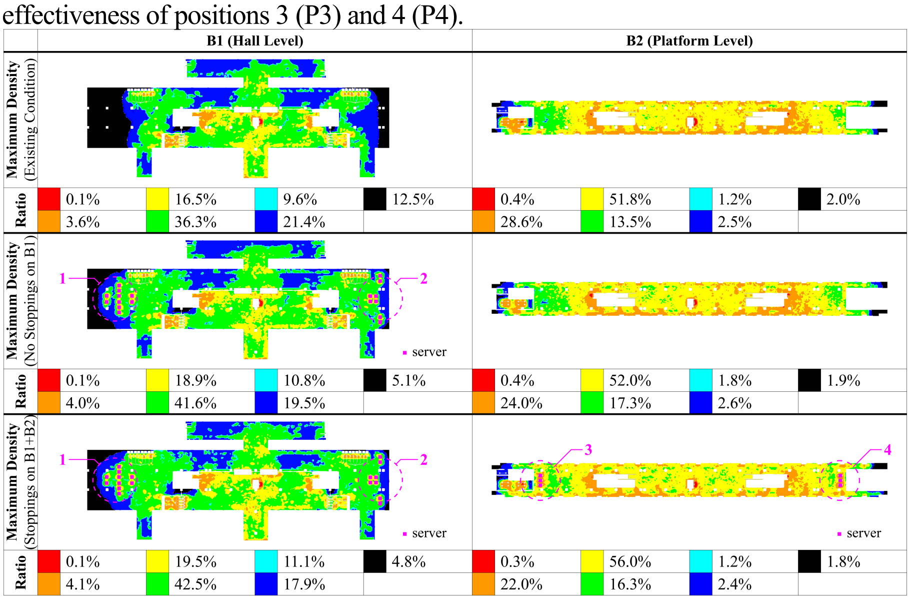

Figure 6. Position Analysis & Validation

6.3. OPTIMIAZATION II: DETAILED LAYOUTS

While maintaining the same "I"-shaped layout for P2, P3, and P4, and an equal number of stopping points for each position within each layout type, we categorized the model into Type 1("三"-shaped), Type 2 ("C"-shaped), and Type 3 (open retail space mixed with retail units) based on different layout of P1. Subsequently, simulations were conducted for each type, and the results are illustrated in Figure 7. A comparison with the existing conditions in Section 6.2 reveals that the first two layouts can significantly alleviate congestion in B2. Type 2 not only exhibits a slight advantage in controlling the red zone but also demonstrates a practice of placing retail units as close to the walls as possible, which can, to some extent, reduce the occurrence of moderate congestion (orange and yellow zones). In comparation between the two layout types, Type 2 outperforms Type 1. Type 3 is less effective in addressing congestion in B1 compared to the first two types but approaches their performance in B2.

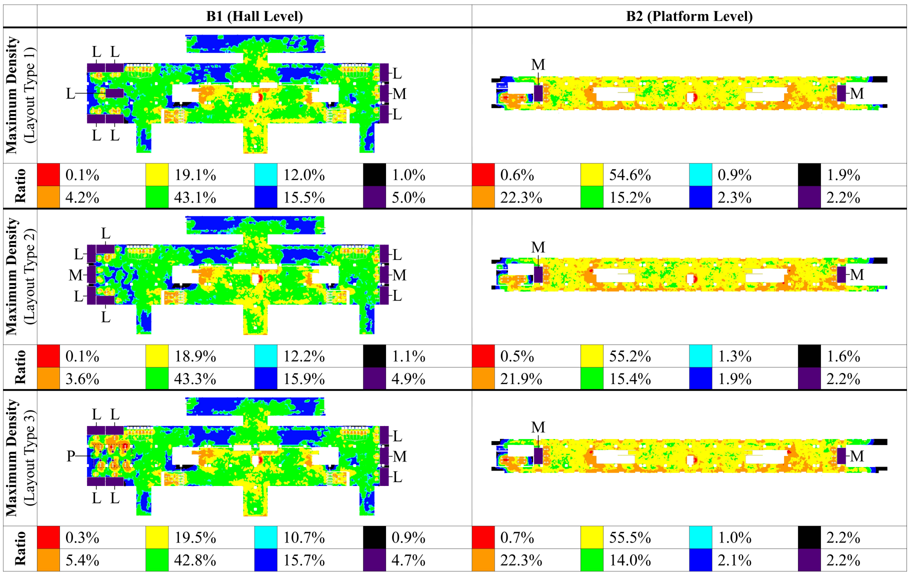

Figure 7. Crowding Evaluation Results of Proposed Layout Types

As shown in Figure 8, we conducted a visual analysis of the station based on its current situation. Simultaneously, we performed a visual analysis of each layout configuration based on the content shown in Figure 7. Figure 9 respectively illustrates the visual simulation results of the proposed retail zone configuration. In comparation to the existing conditions, the results for all three types demonstrate an increase in vision count and vision time (these positions are marked as magenta circles in Figure 9). The increases for the first two types are relatively small, and Type 2 performs significantly better than Type 1 on P1. The introduction of open retail space in Type 3 significantly enhances the vision count and vision time in that area, yielding results much superior to the first two types. Therefore, Type 3 has the potential to improve the visibility of retail units further away, potentially increasing the consumer visits. It is also worth noting that, as these three types share the same layout in B2, the differences in their results are relatively small.

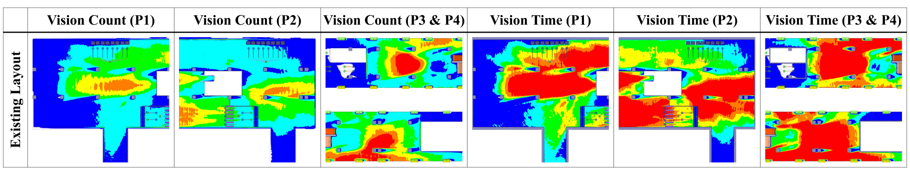

Figure 8. Visibility Evaluation Results of Existing Layout

In summary, when employing a layout with traditional retailed units, Type 2 is a preferable choice, while applying Type 3 can significantly enhance commercial vitality, though with a slightly weaker impact on congestion control in B1.

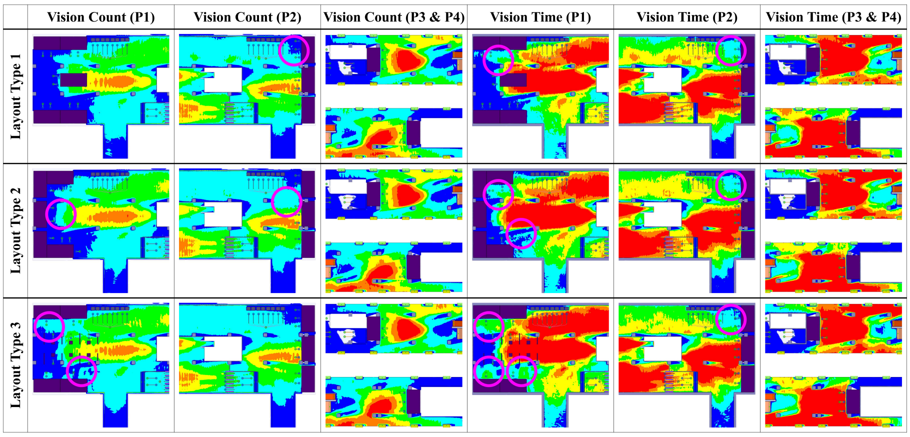

Figure 9. Visibility Evaluation Results of Proposed Layout Types

7. Conclusion

Through the ABM approach based on MassMotion, we propose a framework that relies on visual and density analysis to provide layout decisions and optimization recommendations for incorporating retail space into existing subway stations. The efficiency of this evaluation and optimization approach was validated through simulations conducted at Xiyuan Station. The results indicate that placing modular retail space with "C"-shaped (as P1 in Type 2) or "I"-shaped (as P2, P3, P4) layouts along the walls at both ends of the station hall and platform in low-density areas does not contribute to additional congestion during peak hours. Instead, it effectively reduces platform congestion by attracting passengers to linger, thereby achieving staggered flow. Importantly, combining these units with open retail spaces (such as pop-up stores) significantly increases the likelihood of attracting passenger attention, therefore enhancing the potential for passenger consumption. Firstly, the application of this framework holds promise for guiding the commercial renovations of existing subway spaces, offering a viable solution for reducing subway congestion, increasing non-ticket revenue, and optimizing the profitability model of the subway. Secondly, this approach proves beneficial in assisting with preliminary scheme design and decision-making before design, as well as in evaluating and modifying scheme after design. We envision with optimism that public transportation, as an environmentally and socially inclusive mode of transportation, can contribute to sustainable development by reducing car dependency and carbon emissions through this approach.

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