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Flexible Land-Use Control Planning for Bus Terminals at Mega Railway Hubs: An AI-Enabled Approach

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Abstract

In recent years, bus terminals serving mega railway hubs in China's major cities and megacities have faced a prominent contradiction between declining passenger demand and redundant land provision. This study examines four benchmark railway hubs in China and abroad and shows that three land-use optimization strategies-distributed layout, functional sharing, and three-dimensional integration-can substantially reduce terminal land requirements while maintaining essential feeder-transport functions, thereby providing an alternative to the conventional approach of sizing land solely from peak passenger demand. On this basis, a flexible land-use control model is developed by dividing terminal land into rigid service space and flexible adjustment space. The former is sized against off-peak passenger demand to meet basic operational needs, while the latter accommodates peak-period reserve capacity, mixed-use functions, and long-term development reserves. The study also explores an implementation pathway supported by deep learning and video-image recognition technologies and establishes an operational mechanism that integrates AI-enabled multi-source data acquisition, passenger-flow prediction, dynamic spatial regulation, and closed-loop feedback. This framework shifts bus-terminal land-use control from a static and rigid model toward dynamic and adaptive spatial governance. The findings provide a conceptual and methodological reference for intensive land use and adaptive planning of bus terminals at mega railway hubs.

Keywords

Railway Hub; Bus Terminal; Land-Use Control Planning; Artificial Intelligence; Image Recognition.

1. Introduction

With the continuous expansion and maturation of China's high-speed railway network, railway hubs are gradually evolving from single-purpose passenger collection and distribution nodes into multifunctional, integrated station-city complexes. Regardless of the development model adopted, surface bus terminals remain essential feeder facilities for distributing rail passenger flows and connecting passengers with urban transportation services. The spatial layout and land-use control requirements of bus terminals directly affect the efficiency of land utilization within railway hubs and the quality of passenger transfers and overall travel experience [1].

At present, many railway hubs, particularly mega-scale hubs, size bus-terminal land primarily on the basis of peak passenger demand. As a result, land reserves are often oversized, with bus facilities often occupying separate sites and being distributed across multiple levels (see Table 1). This pattern is increasingly at odds with the continued decline in conventional urban public-transit ridership in China's major megacities (see Fig. 1), giving rise to typical resource-allocation imbalances such as

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"large stations with low passenger demand," "redundant land provision," and "rigid functional configurations." Against this background, this study draws on land-use control practices at benchmark railway hubs in China and abroad and explores a new planning and land-use control framework for railway feeder bus terminals that is flexible and dynamically adaptable.

Table 1. Land-use scale of bus terminals at selected large and mega railway hubs in China

Railway hub	Layout form	Terminal area (m^2)	Routes	Area per route (m^2/route)
Guangzhou East Railway Station	Independent site; at-grade layout	20,000	41	500
Wuhan Railway Station	Independent site; at-grade layout	22,000	14	1,570
Zhengzhou Railway Station	Independent site; at-grade layout	40,000	23	1,740

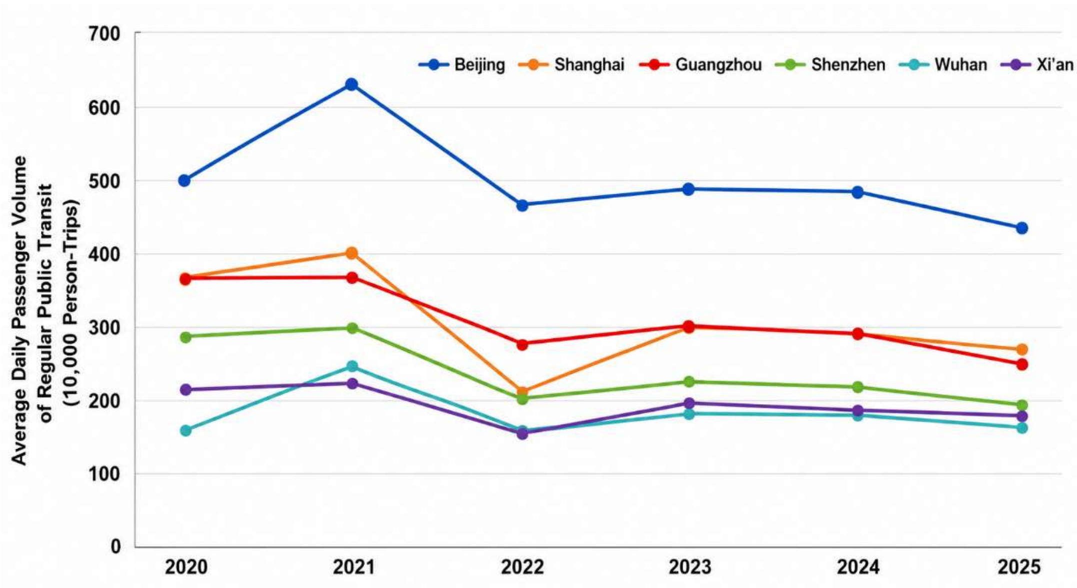

Fig. 1 Average daily conventional bus ridership in selected Chinese cities, 2020–2025

2. Bus-Terminal Layout Patterns at Benchmark Railway Hubs in China and Abroad

2.1 Tokyo Station, Japan

Tokyo Station [2], located east of the Imperial Palace in Japan, comprises the Marunouchi and Yaesu station buildings. It has 14 platforms and 28 tracks and serves seven Shinkansen lines, nine JR lines, and one urban rail line, with an average daily passenger volume of approximately 430,000. As Japan's largest railway station, Tokyo Station is closely integrated with surrounding urban functions, featuring mixed land uses and a high development intensity. Ground-level feeder transport is dominated by walking, with buses playing a supplementary role. Within approximately 300 m of the station, nine bus boarding areas are distributed, serving intercity coaches, conventional buses, sightseeing services, and free shuttle services. Conventional bus services are distributed around the Marunouchi and Yaesu station-front plazas, with an average headway of 3-5 min.

The Yaesu station-front plaza accommodates four types of transport facilities:ground-level buses, intercity coaches, taxis, and private cars,within a compact area of 0.87 ha. Ground-level bus services use three berths for three routes, while intercity coaches use nine berths serving 24 routes; buses and intercity coaches together occupy approximately 0.2 ha. The entire station-front plaza adopts a multi-access, one-way circulation pattern to reduce conflicts among different traffic flows (see Fig. 2).

Volume 12 Issue 8, 2026
DOI: 10.6919/ICJE.202608_12(8).0002

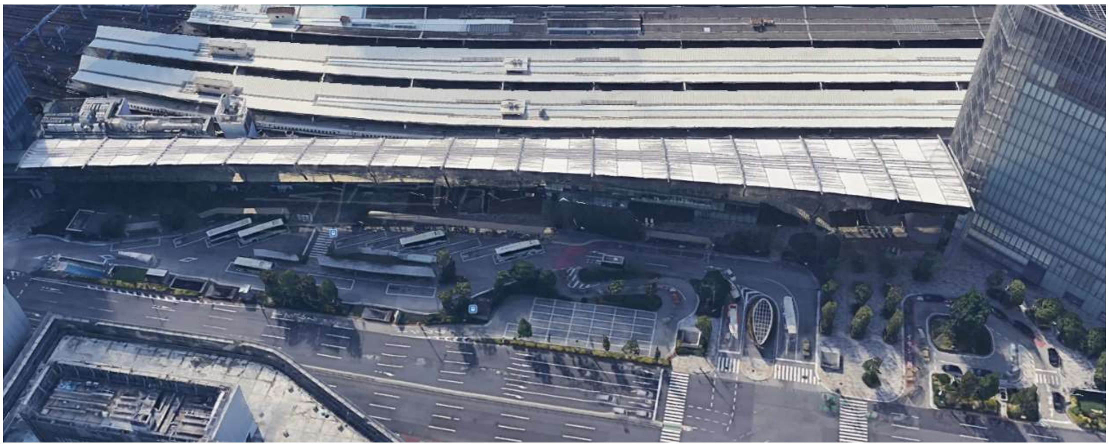

Fig. 2 Bus-terminal layout at Tokyo Station

2.2 Hong Kong West Kowloon Station

Hong Kong West Kowloon Station [3] is located in the urban core between Kowloon Station and Austin Station. It is the terminus of the Guangzhou–Shenzhen–Hong Kong Express Rail Link and Hong Kong's only high-speed rail gateway. The station commenced operation in 2018 and handles approximately 140,000 passengers per day. It is the world's largest underground terminus-type railway station, with 12 platforms and 15 tracks. Seven platforms and six tracks serve short-haul trains with eight-car formations to and from Guangzhou, Dongguan, and Shenzhen, while five platforms and nine tracks serve long-distance trains with 16-car formations to destinations across China. The station adopts a strategy of "creating space through vertical integration," comprising four underground levels and two above-ground levels with a total floor area of approximately 430,000 m². Railway and road underpasses restore the ground-level urban fabric and reconnect the station with Victoria Harbour. A multidimensional pedestrian system, particularly an elevated pedestrian network, strengthens the connection between the transport hub and surrounding urban areas. Above-station development is primarily office-oriented, with podium-level commercial facilities serving business users and high-speed rail passengers.

Ground-level bus services at the hub adopt a "one terminal + N intermediate stops" layout. A bus terminal and sightseeing-bus parking area are located north of the hub; a public transport interchange is located on the west side; and intermediate stops are distributed on the east and northeast sides. The bus terminal provides 10 boarding/alighting berths and 18 layover berths, occupies approximately 0.5 ha, and adopts one-way traffic organization. It serves 11 routes, including three trunk bus routes and 11 feeder routes, and shares the site with 30 sightseeing-bus parking spaces (see Fig. 3).

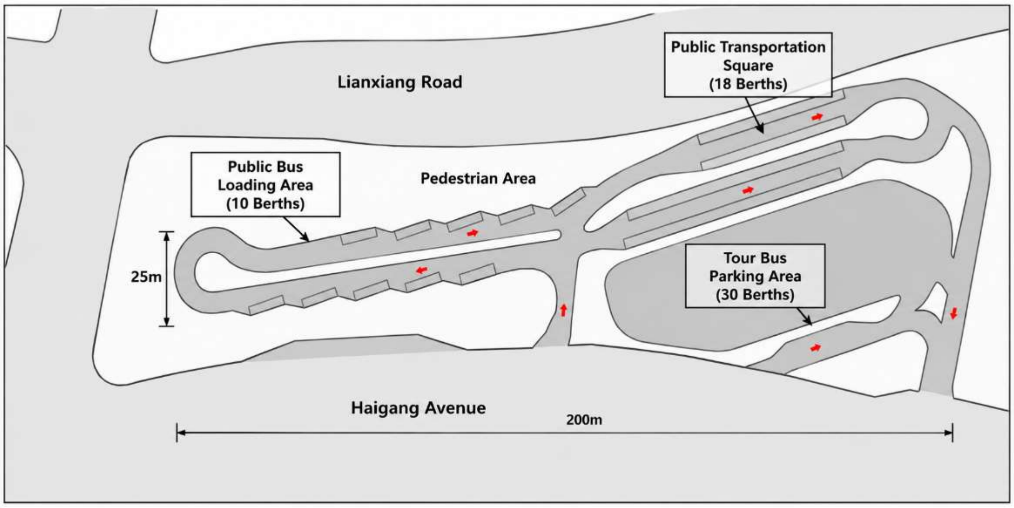

Fig. 3 Schematic Layout of the Bus Terminus at West Kowloon Station

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2.3 Shenzhen North Railway Station

Shenzhen North Railway Station [4] is an integrated transport hub in Longhua District, approximately 9.3 km from central Shenzhen. It is China's first railway station with an elevated-track, elevated-access configuration. The station connects the Beijing–Guangzhou High-Speed Railway, Guangzhou–Shenzhen–Hong Kong High-Speed Railway, Shenzhen–Hangzhou High-Speed Railway, Nanning–Guangzhou Railway, Guiyang–Guangzhou Railway, and other lines. It has 11 platforms and 20 tracks and handles approximately 380,000 passengers per day. Its total floor area is about 667,000 m², including 180,000 m² for the national railway hub, 410,000 m² for supporting hub facilities, and 77,000 m² for integrated development above the hub. Intercity coaches, taxis, private cars, and buses are distributed around the four corners of the railway station building (see Fig. 4), while Metro Lines 4, 5, and 6 handle a large proportion of railway passenger transfers.

The bus terminal is located in the northeast quadrant of the East Plaza and comprises three levels. It is organized by level according to the principle of "bus rapid transit–trunk buses–feeder buses," with ramps connecting the levels. The bus waiting areas adopt an island layout with platform screen doors, and each level is connected to the integrated transfer hall, improving passenger comfort and safety. The terminal occupies approximately 1.1 ha and has a floor area of 34,000 m², providing 74 bus berths for more than 20 routes (see Fig. 4).

Fig. 4 Bus-terminal layout at Shenzhen North Railway Station

2.4 Guangzhou Baiyun Railway Station

Guangzhou Baiyun Railway Station [5] is one of the principal hubs in Guangzhou's "five main + four auxiliary" railway-hub system and is a core project for bringing high-speed rail services into Guangzhou's urban area. It serves six major railway corridors, including the Beijing–Guangzhou High-Speed Railway, Guangzhou–Shantou High-Speed Railway, Guangzhou–Zhanjiang High-Speed Railway, Beijing–Guangzhou Railway, Guangzhou–Shenzhen Railway, and Guangzhou–Maoming Railway. The station has 11 platforms and 24 tracks, with peak-day passenger volumes exceeding 200,000. Intercity coaches, taxis, private cars, and bus terminals are arranged in a three-dimensional configuration around the railway station building. Metro Lines 8 and 12 are connected to the hub and provide efficient transfers, making it a modern integrated transport hub incorporating high-speed rail, conventional rail, intercity rail, metro, and urban bus services.

The supporting bus terminal is located at the northwest corner of the railway station building and provides boarding/alighting, bus layover, and supporting services. It occupies an independent site of

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approximately 1.7 ha, including a 0.3-ha core-tube area required for the development above the terminal. The terminal has a floor area of approximately 25,000 m² and includes 73 layover berths and 22 boarding/alighting berths serving 25 routes. It is arranged over three levels. In addition, approximately 61,200 m² of above-terminal property development has been constructed (see Fig. 5).

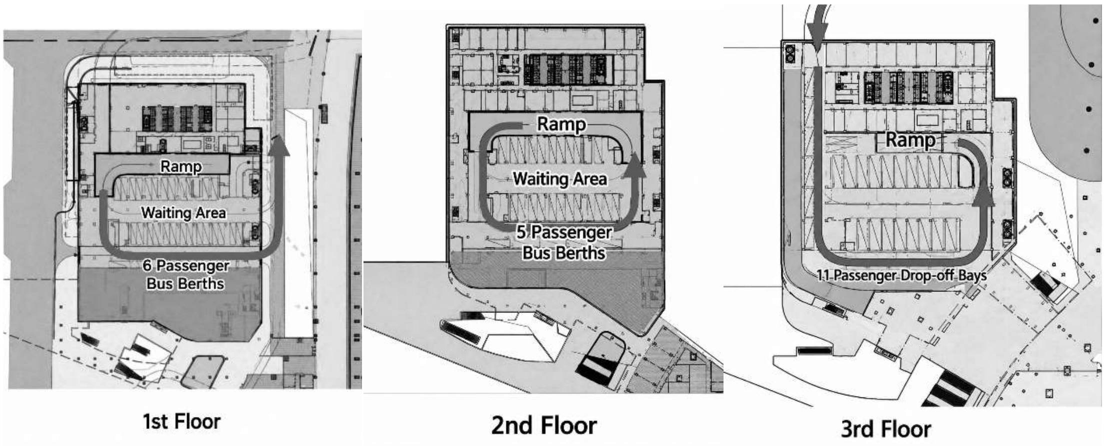

Fig. 5 Schematic Layout of the Bus Terminal at Guangzhou Baiyun Station

3. Land-Use Control Practices and Planning Implications from Benchmark Railway Hubs

3.1 Summary of Land-Use Control Practices

A comparison of the four railway-hub bus-terminal cases reveals three major shifts from conventional railway feeder bus terminals:

(1) From centralized provision to distributed layout. Conventional railway-hub bus terminals generally adopt centralized terminal layouts, where dozens of bus routes originate and terminate and various operational management facilities, such as dispatching and staff rest rooms, are provided. This results in highly integrated functions and relatively large land requirements. However, the cases above indicate that the core passenger-collection and distribution system of mega railway hubs is increasingly dominated by rail transit and private cars. With the continuous expansion of urban rail networks, growth in private-car travel, increasing scarcity of urban land, and tighter land-use constraints, the traditional large-scale centralized bus-terminal model is becoming less compatible with current development needs. Ground-level buses should therefore shift toward a supplementary passenger-collection and distribution role. Distributed stop layouts can substantially reduce land consumption while maintaining the traffic efficiency and service functions of bus access to railway hubs.

(2) From single-function use to functional sharing. Tokyo Station and Hong Kong West Kowloon Station both emphasize shared use of transport space. Unlike conventional bus terminals that serve buses exclusively, the bus spaces in these benchmark hubs can accommodate sightseeing buses, public rest areas, and other functions according to demand. At the same time, internal vehicle circulation and physical separation between pedestrians and vehicles should be carefully designed to reduce interference among conflicting traffic flows and improve vehicle turnover efficiency as well as passenger safety and comfort.

(3) From at-grade land occupation to three-dimensional integration. Practices at newly built railway hubs such as Shenzhen North and Guangzhou Baiyun demonstrate that bus terminals can overcome the limitations of conventional two-dimensional land-use control and shift toward three-dimensional spatial organization. By arranging and integrating passenger waiting areas, vehicle parking and circulation spaces, operational dispatch spaces, and commercial/business service spaces across different levels, the ground-level footprint can be substantially reduced while core functions such as

Volume 12 Issue 8, 2026
DOI: 10.6919/ICJE.202608_12(8).0002

passenger collection and distribution and vehicle operation and maintenance are retained. This model not only improves the capacity and service quality of bus access to railway hubs, but also promotes the coordinated integration of transport infrastructure with urban supporting functions, with diversified urban services in turn supporting hub operations and district development.

3.2 Case Implications

The three shifts described above represent an iterative upgrade in land-use control planning for railway-hub bus terminals from the perspectives of layout pattern, functional system, and spatial utilization. They effectively address the problems of extensive land use, single-function configurations, and insufficient adaptability associated with traditional terminals. Compared with Table 1, they substantially reduce bus-berth requirements and overall land demand. In practical terms, bus terminals using a separated terminal-and-stop arrangement can generally control land requirements within 5,000 m², while terminals using an integrated terminal-and-stop arrangement can generally control land requirements within 15,000 m² (see Table 2). It should be noted that land control for bus terminals at mega railway hubs is not simply a matter of reducing construction scale or minimizing land. Rather, it should enhance spatial adaptability and long-term resilience while ensuring core transport functions such as passenger collection and distribution and operational services. Accordingly, land-use control should shift from the rigid model of "forecasting peak demand and maximizing land provision" toward a flexible planning model of "consolidating basic service demand and reserving dynamically convertible space."

Table 2. Land-use scale of five benchmark mega railway-hub bus terminals

Hub case	Terminal layout mode	Spatial functions	Terminal area (m²)
Tokyo Station, Japan	Independent site; at-grade; terminal-stop separation; multiple locations	Shared transport space for buses and other modes	2,000
Hong Kong West Kowloon Station	Independent site; at-grade; terminal-stop separation	Shared transport space for buses and sightseeing coaches	5,000
Shenzhen North Railway Station	Independent site; three-dimensional; terminal-stop integration	Multi-level bus facilities; separated boarding/alighting	11,000
Guangzhou Baiyun Railway Station	Independent site; three-dimensional; terminal-stop integration	Multi-level bus facilities compatible with above-terminal development	14,000

4. Delineation of Rigid and Flexible Space for Railway-Hub Bus Terminals

4.1 Concept of Flexible Land-Use Control Planning

Flexible land-use control refers to the layered allocation and dynamic management of terminal land resources based on basic bus-terminal operational needs, passenger-flow variation patterns, traffic-organization requirements, and urban spatial-development conditions, thereby providing transport facilities with a certain capacity for adaptive adjustment and replacing the traditional practice of allocating land once according to maximum demand.

Based on terminal functions and future change characteristics, this study divides bus-terminal planning land into rigid service space and flexible adjustment space and establishes the following flexible land-use control model:

$$S = S_r + S_e$$

where: S is the total planned land area of the bus terminal; S_r is rigid service space; and S_e is flexible adjustment space.

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4.2 Rigid Service Space S_r

At the terminal-scale calculation level, this study abandons the conventional approach of using peak-hour passenger demand for spatial projection and instead uses normal passenger demand during off-peak periods as the basic parameter for calculating the operational space required for bus vehicle operations. This avoids excessive terminal land reservation caused by short-duration peak passenger flows. For supporting facilities, the two development modes-bus-terminal separation and bus-terminal integration-are used as the classification framework. National industry standards, local construction standards, and planning guidelines [6–13] are comprehensively compared to identify mandatory, optional, and unnecessary facilities under the two modes across four functional modules: information facilities, convenience facilities, safety and environmental-protection facilities, and operational management facilities. Differences in configuration levels for vehicle parking, vehicle maintenance, charging/swapping, and lane arrangements are also identified. The resulting complete facility configuration lists for integrated and separated bus-terminal modes (see Fig. 6) provide a standardized reference for the composition and spatial allocation of rigid service space under different development modes.

4.3 Flexible Adjustment Space S_e

Flexible adjustment space is the key spatial carrier for optimizing the traditional fixed bus-terminal planning paradigm. It complements the functionally stable and fixed-purpose rigid service space. Its defining feature is that it supports mixed-use development during normal off-peak periods and can rapidly switch functions and release operational space during peak passenger-flow periods to respond to dynamic fluctuations in demand. Based on actual terminal operating scenarios, flexible adjustment space can be divided into three functional categories.

Facility Composition		Separated Bus Station Mode	Integrated Bus Station Mode
Information Facilities	Public information sign	√	√
	Station sign	√	√
	Area map and bus route map	√	√
	Bus timetable	√	√
	Real-time information display	√	√
	Information inquiry facilities	√	√
	Barrier-free facilities	√	√
Convenience Facilities	Parking lot	√	√
	Platform	√	√
	Seating	√	√
	Pedestrian passage	O	O
	Non-motorized vehicle parking	√	√
	Non-motorized vehicle storage	√	√
	Motorized vehicle parking spaces	-	O
Safety & Environmental Protection	Waiting shelter	O	O
	Lighting	√	√
	Surveillance	√	√
	Fire protection	√	√
	Greening*	√/-	√/-
	Environmental protection facilities	√	√
Operational Management	Station control room	√	√
	Line dispatch room	√	√
	Intelligent monitoring room	√	√
	Driver rest room	√	√
	Restrooms	√	√
	Dining area	√	√
	Cleaning tool storage room	√	√
	Return channel	√	√
	Vehicle entrance	√	√
	Waiting area	√	√
	Return aisle	√	√
	Parking space	-	O
	Vehicle maintenance and repair facilities	-	O
	Refueling or charging facilities	-	O

Legend: √ = Required facility O = Optional facility - = Facility not provided

Indicates configuration differences Indicates higher configuration level; darker color represents higher level

Fig. 6 Schematic Recommendations for Configuration Standards under Different Bus Terminal Layout Patterns

The first category is peak-period reserve space, which serves as an emergency buffer and supports passenger-flow diversion during holiday surges and large public events, temporary adjustments to bus-route dispatching, and temporary vehicle parking under unexpected circumstances. The second category is mixed-use space, based on the integration of terminal and urban functions. During non-peak periods, it can accommodate public convenience services, basic commercial facilities, tourism and cultural passenger transfers, and leisure activities, thereby activating the land value of terminal space during idle periods. The third category is long-term conversion reserve space, which is reserved for future transport development and can accommodate parking and charging for autonomous feeder vehicles, emerging urban mobility services, and district renewal, thereby enhancing the full-life-cycle adaptability of bus terminals.

5. AI-Enabled Pathway for Flexible Spatial Planning

Flexible land-use control is a core concept for achieving time-sharing reuse of bus-terminal space and dynamic allocation of long-term reserve areas. Traditional static planning and control approaches are difficult to adapt to complex and changing spatial demands arising from passenger-flow fluctuations, mixed-use development, and emerging transport modes. With the policy-level guidance of China's "Artificial Intelligence + Transportation" initiative [14], digital technologies such as intelligent sensing and digital twins for transport hubs can support the full life cycle of terminal planning, construction, and routine operation. These technologies can help address practical problems including idle terminal land, mismatches between construction scale and demand, and rigid and single spatial functions, and can therefore serve as important technical enablers for implementing flexible land-use control strategies.

On this theoretical basis, this study proposes a digital-technology support pathway for flexible land-use control of bus terminals serving mega railway hubs. An operational mechanism of "multi-source data acquisition–passenger-flow assessment and prediction–dynamic flexible-space regulation–closed-loop feedback iteration" is established on an AI-enabled digital platform (see Fig. 7), promoting a transition from conventional fixed and static land-use control toward dynamic, adaptive, and refined spatial governance in response to passenger-flow fluctuations.

5.1 Multi-Source Data Acquisition

Passenger flows associated with bus transfers at railway hubs exhibit strong temporal variability, sudden surges, and multimodal transfer characteristics. Therefore, operational data should be collected across departments and dimensions. First, railway and metro authorities should be linked to obtain train arrival and departure times, passenger entry and exit volumes, transfer volumes, and related information. AI-based deep-learning analysis can then be used to identify passenger-collection and distribution characteristics at different time scales and detect changes in demand for bus transfers. Second, bus operational data-including vehicle arrival and departure frequency, route operating status, platform utilization, and vehicle queues-should be integrated to enable real-time AI monitoring of terminal operating conditions. Third, video-sensing terminals should be deployed throughout the site. Video-structured AI recognition can be used to identify spatial utilization within the terminal and dynamically detect passenger distribution, passenger density, and passenger trajectories through video and image analytics.

Multi-source data fusion can transform bus-terminal operational monitoring from "manual observation" into "digital perception." Key indicators such as total passenger volume, passenger volume by zone, station entry and exit volumes, passenger density, passenger movement patterns, individual trajectories, and video-monitoring data can be intelligently collected, providing a data foundation for dynamic passenger-flow perception at railway hubs.

5.2 Passenger-Flow Analysis and Prediction

Passenger-flow trend prediction. Reinforcement learning can be applied to the collected passenger-volume and passenger-behavior data. By integrating historical operating data, train operating plans,

 Volume 12 Issue 8, 2026
DOI: 10.6919/ICJE.202608_12(8).0002

holiday effects, weather conditions, and urban-event impacts, AI models can predict passenger volumes at different future time scales, providing a basis for assessing bus-terminal spatial demand.

Spatial load assessment. Indicators such as passenger density, number of waiting passengers, and vehicle turnover efficiency can be combined to evaluate the carrying capacity of different terminal functional areas and identify areas with insufficient capacity or low utilization efficiency.

Demand-level identification. Based on predicted passenger volumes and spatial pressure, terminal operating conditions can be classified into three levels-off-peak, peak, and emergency-providing the basis for activating flexible space.

5.3 Dynamic Spatial Adjustment

During off-peak periods, rigid service space meets basic bus-operational requirements, while flexible adjustment space can accommodate public activities, urban services, and other mixed uses, thereby improving the overall efficiency of land utilization.

As railway arrival and departure passenger volumes increase and bus-transfer demand reaches peak levels, the system issues warnings based on passenger density, vehicle queuing, and spatial utilization conditions and activates part of the flexible space, converting it into temporary waiting areas, bus-organizing areas, and other operational spaces to enhance terminal service capacity.

During major public events, extreme weather, or unexpected traffic incidents, an emergency spatial-conversion mechanism is activated to rapidly adjust vehicle organization, passenger evacuation, and spatial layouts.

5.4 Development of a Digital Platform

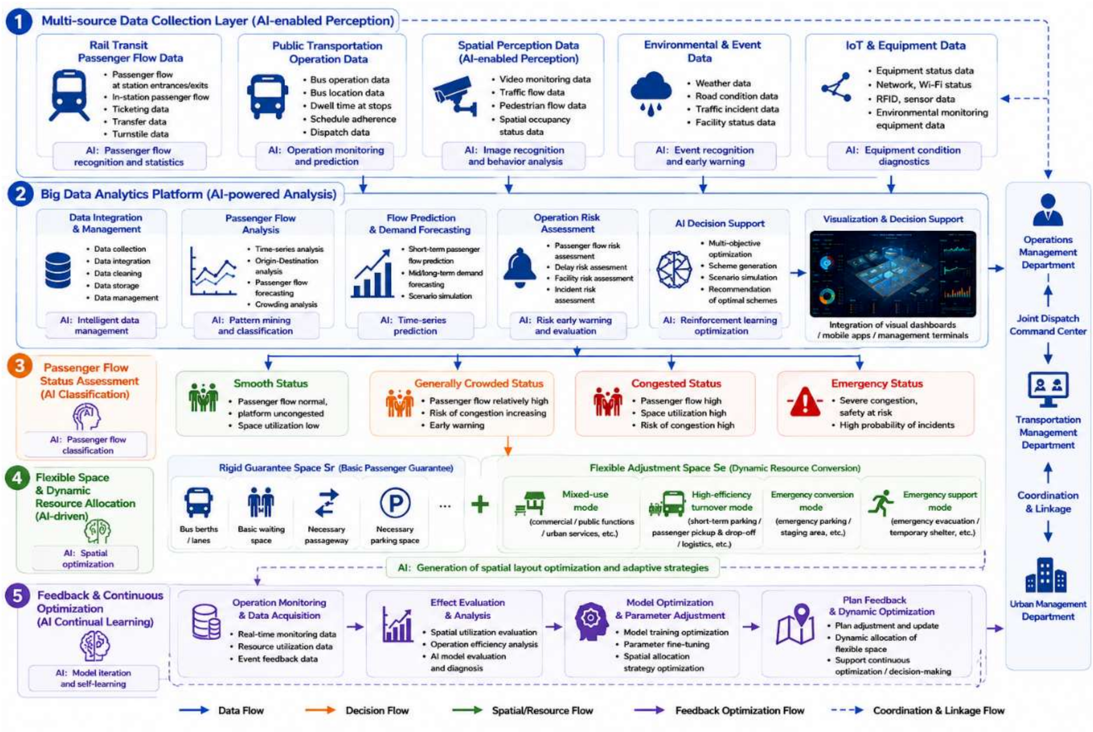

Fig. 7 AI-Assisted Flexible Land-Use Control Mechanism for Bus Terminals at Mega-Scale Railway Hubs

(Source: Drawn by ChatGPT at the author's request.)

To support the functions described above, an AI-enabled digital platform should be developed to support flexible land-use control. First, a digital-twin model of the bus terminal should be established. BIM and GIS technologies can be used to digitally represent terminal spatial layouts, transport facilities, and operational conditions, enabling visualized management of spatial resources. Second,

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a spatial-utilization evaluation system should be established. AI-based video and image recognition can continuously collect data on passenger volumes, spatial utilization rates, vehicle operating efficiency, and other indicators, while deep learning and AI large models can be used for data prediction and dynamic evaluation of the appropriateness of rigid and flexible space allocation, providing a basis for subsequent planning adjustments. Finally, a planning feedback and optimization mechanism should be established. Operational data accumulated during the operation phase can be used to continuously update passenger-flow prediction models, allowing bus-terminal plans to evolve in response to urban development and changing transport demand.

6. Conclusion and Directions for Future Research

Through a comparative analysis of four benchmark railway hubs in China and abroad, this study demonstrates the effectiveness of three land-use optimization strategies-distributed layout, functional sharing, and three-dimensional integration-and provides a planning perspective distinct from the conventional approach of determining terminal area based primarily on peak passenger demand. On this basis, a flexible land-use control model is developed by dividing terminal land into rigid service space and flexible adjustment space. Rigid space is calculated using off-peak passenger demand as the benchmark and is standardized through categorized facility configuration requirements, while flexible space accommodates three functions: peak-period reserve, mixed use, and long-term reserve. This provides a quantitative basis for layered land-use control and time-sharing reuse of terminal land.

The study also develops an AI-enabled implementation pathway and establishes an operational mechanism integrating AI-based video and image recognition, multi-source data acquisition and deep learning, passenger-flow analysis and prediction, dynamic spatial regulation, and closed-loop feedback through a digital platform. This extends flexible land-use control from a spatial concept into an operational model of dynamic governance. Future research should calibrate model accuracy using measured operational data, select actual terminals for pilot validation, quantify the land-saving and operational-efficiency benefits generated by flexible land-use control, and further investigate its compatibility with emerging feeder-transport modes.

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