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DYNAMIC EARLY WARNING MODELING OF PASSENGER AGGREGATION RISK AT RAILWAY PASSENGER HUBS

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Abstract: Under conditions such as holiday travel peaks, concentrated train arrivals and departures, and operational disturbances, railway passenger hubs are prone to localized passenger aggregation in key areas such as security checkpoints, waiting halls, ticket gates, and platforms, which may further lead to congestion propagation and operational risk. To address the limitations of existing studies, including insufficient focus on railway passenger hub scenarios, inadequate dynamic characterization of risk identification, and limited management orientation of warning results, this study investigates the dynamic early warning of passenger aggregation risk at railway passenger hubs. First, the formation mechanism of passenger aggregation risk is analyzed from the perspectives of passenger demand fluctuations, facility service capacity constraints, and operational disturbance propagation, and a risk indicator system is established from three dimensions: passenger-state conditions, facility operations, and disturbance factors. On this basis, a dynamic early warning framework consisting of data input, state identification, risk assessment, and warning output is proposed to support graded identification and dynamic response for passenger aggregation risk in key functional areas. Finally, an illustrative case study is conducted to demonstrate the applicability of the proposed framework. The results show that passenger aggregation risk at railway passenger hubs exhibits significant time-varying, spatially heterogeneous, and propagative characteristics, while bottleneck areas such as security checkpoints and ticket gates are more sensitive in both risk formation and escalation. The proposed framework is capable of representing the evolution of risk and translating operational states into graded warning results with direct managerial relevance. This study provides theoretical support and methodological guidance for passenger flow safety management and operational optimization at railway passenger hubs.
Keywords: Railway passenger hubs; Passenger aggregation risk; Dynamic early warning; Risk assessment

1 INTRODUCTION

With the continuous expansion of high-speed rail networks and the increasing integration of multimodal transportation systems, railway passenger hubs have become critical nodes for passenger gathering, transfer, and operational coordination[1-2]. During holiday peaks, concentrated train arrivals and departures, and service disruptions, passengers tend to accumulate rapidly in key areas such as security checkpoints, waiting halls, ticket-checking gates, platforms, and connecting corridors. Such passenger aggregation not only reduces operational efficiency and service quality, but also increases the likelihood of blocked circulation, localized congestion, and even safety incidents[3-4]. Therefore, accurately capturing the formation and evolution of passenger aggregation risk and providing timely dynamic early warning have become essential for ensuring the safe and efficient operation of railway passenger hubs.

Existing studies have generated substantial insights into passenger flow characteristics, short-term flow prediction, crowding identification, and risk assessment in transport facilities, providing an important foundation for crowd safety management. However, several limitations remain. First, much of the existing literature focuses on forecasting passenger volumes or identifying crowding conditions, while insufficient attention has been paid to the more management-oriented problem of passenger aggregation risk early warning[5]. Second, many studies rely on static thresholds or single indicators for risk judgment, which makes it difficult to capture the dynamic spatiotemporal evolution of passenger aggregation within railway passenger hubs. Third, compared with urban rail transit scenarios, research specifically targeting railway passenger hubs is still relatively limited, and the combined effects of train schedule fluctuations, facility capacity constraints, and multi-area interactions have not yet been adequately addressed.

To address these gaps, this study focuses on the dynamic identification and early warning of passenger aggregation risk at railway passenger hubs. First, the formation mechanism of passenger aggregation risk is analyzed from the perspectives of demand fluctuations, service capacity constraints, and disturbance propagation, and key indicators characterizing risk states are identified. On this basis, a dynamic early warning framework is developed to support the identification, assessment, and graded warning of passenger aggregation risk in railway passenger hubs. Finally, a case study is conducted to verify the applicability and effectiveness of the proposed framework. The findings of this study are expected to provide theoretical support and practical guidance for passenger flow safety management and operational optimization in railway passenger hubs.

2 RISK ANALYSIS AND DYNAMIC EARLY WARNING FRAMEWORK

2.1 Risk Analysis of Passenger Aggregation at Railway Passenger Hubs

Passenger aggregation risk at railway passenger hubs is not triggered by a single factor; rather, it results from the combined effects of demand fluctuations, facility service capacity constraints, and operational disturbances[6]. Compared with urban rail transit stations, railway passenger hubs are characterized by more concentrated train arrivals and departures, longer passenger dwelling times, more complex functional zoning, and stronger interactions among different areas. As a result, passenger aggregation risk in railway hubs tends to exhibit stronger temporal concentration, spatial heterogeneity, and propagation effects. When a large number of passengers enter the hub within a short period, or when disturbances such as train delays and changes in ticket-checking organization occur, rapid passenger accumulation may arise in key areas including security checkpoints, waiting halls, ticket-checking gates, platforms, and connecting corridors, thereby reducing local circulation efficiency and increasing risk levels.

From the perspective of formation mechanism, passenger aggregation risk at railway passenger hubs can be understood from three aspects. First, demand-side fluctuations serve as the direct trigger of risk, including holiday surges, concentrated train arrivals and departures, and short-term peaks in passenger inflow, all of which can significantly increase local crowd pressure within a limited time period[7]. Second, facility capacity constraints are a major factor in risk escalation. Facilities such as security checkpoints, ticket gates, escalators, stairways, and waiting spaces all have limited service capacities. Once the passenger arrival rate continuously exceeds the local handling capacity, queues, dwell times, and congestion begin to accumulate. Third, disturbance propagation effects make the risk inherently dynamic. Passenger accumulation in one area not only affects local operations, but may also spread to adjacent areas through passenger movement and time-lagged interactions, thereby generating a wider range of aggregation risk.

Based on the above analysis, this study considers passenger aggregation risk at railway passenger hubs as a spatiotemporally dynamic risk state, whose essential characteristics can be summarized as local formation, dynamic evolution, and inter-area propagation. Therefore, such risk cannot be effectively identified through static threshold judgment alone. Instead, it should be characterized by multiple dimensions, including passenger flow conditions, facility load, and operational disturbances. In this context, indicators such as passenger volume, density, speed, and queue length can be used to represent passenger flow states; facility utilization and space occupancy can be used to reflect operational constraints; and train arrival-departure intensity, delay conditions, and short-term fluctuations can be used to capture disturbance effects. These indicators together provide the basis for subsequent dynamic early warning.

2.2 Dynamic Early Warning Framework

Based on the formation mechanism of passenger aggregation risk, this study develops a dynamic early warning framework oriented toward changes in the operational states of key areas within railway passenger hubs[8]. The framework relies on multi-source data and enables the identification, assessment, and graded warning of passenger aggregation risk through continuous state perception and integrated risk characterization. In general, the proposed framework consists of four basic components: data input, state identification, risk assessment, and warning output.

At the data input stage, the framework integrates information that reflects hub operating conditions, including passenger flow monitoring data, facility operation data, and train operation information. These data jointly constitute the input basis for dynamic early warning. At the state identification stage, passenger aggregation conditions are characterized using indicators such as passenger volume, density, speed, and queue conditions in key areas, so as to identify abnormal changes or early signs of potential risk. At the risk assessment stage, passenger-state indicators, facility-operation indicators, and disturbance indicators are jointly analyzed to generate a quantitative or semi-quantitative representation of the risk level in each area and each time interval, thereby capturing the dynamic evolution of passenger aggregation risk. Finally, at the warning output stage, different warning levels are determined according to the assessed risk level and translated into warning information that can support on-site organization and passenger flow management.

Compared with conventional static warning approaches, the dynamic early warning framework proposed in this study emphasizes two key features. On the one hand, risk identification is time-varying, meaning that the assessed risk level and warning results can be continuously updated as passenger flow conditions and operational states change. On the other hand, risk judgment is regionally connected, meaning that the framework not only focuses on the crowd state of an individual area, but also takes into account the interactions and propagation effects among different areas. Under this framework, passenger aggregation risk in railway passenger hubs can be identified in a more timely and systematic manner, providing a theoretical basis for the subsequent case study and warning application.

3 CASE STUDY

3.1 Study Scenario and Data Description

To validate the applicability of the proposed dynamic early warning framework for passenger aggregation risk at railway passenger hubs, an illustrative peak-period case is constructed in this study. The case focuses on the most representative functional chain in the passenger movement process, including the entrance hall, security check area, waiting hall, ticket gates, and platform. These areas constitute the main passenger movement path from station entry to boarding and are also the key spatial units in which passenger accumulation and risk propagation are most likely to occur. Compared with ordinary stations, passenger flow operations in railway passenger hubs are characterized by a strong sequential structure, in which the operating state of upstream areas directly affects the load level of downstream areas. Therefore, the above area selection is well suited to represent the formation and transmission of passenger aggregation risk in a hub environment.

Figure 1 presents the spatial layout of the key functional areas considered in the case study. As shown in the figure, the passenger movement path generally follows the sequence of entrance hall → security check → waiting hall → ticket gates → platform, with connecting corridors linking adjacent operational units. In practice, when concentrated train departures or operational disturbances occur, aggregation risk often emerges first at bottleneck locations such as security checkpoints or ticket gates and then spreads toward the waiting hall, corridors, and platform areas. This layout therefore provides a clear basis for examining both localized congestion formation and inter-area risk transmission.

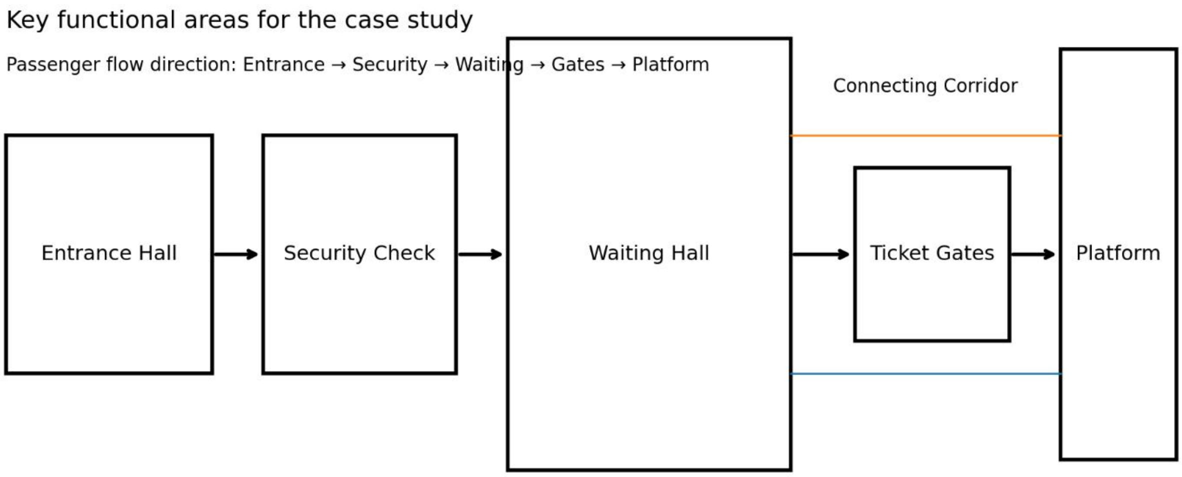

Figure 1 Spatial Layout of Key Functional Areas in the Case Study

From a data perspective, the case study integrates three categories of information: passenger monitoring data, facility operation data, and train operation data. Passenger monitoring data are used to describe passenger volume, density, walking speed, and queue conditions in each area over time. Facility operation data characterize the service capacity and utilization level of key facilities such as security checkpoints, ticket gates, and corridors. Train operation data are introduced to capture the impact of train arrival-departure concentration and delay disturbances on passenger aggregation. To ensure that the temporal evolution of risk can be adequately captured, a 5 min time interval is adopted as the basic analytical unit.

Table 1 Data Structure Used in the Case Study

Data category	Variable	Description	Time resolution	Role in warning
Passenger monitoring data	Passenger volume	Number of passengers entering, staying, or passing through each area	5 min	Reflects local flow pressure
Passenger monitoring data	Density	Number of passengers per unit area	5 min	Measures aggregation intensity
Passenger monitoring data	Walking speed	Average movement speed in each area	5 min	Reflects circulation efficiency
Passenger monitoring data	Queue length	Queue size at security check or ticket gates	5 min	Indicates accumulation and dwell
Facility operation data	Security capacity utilization	Ratio of actual throughput to security capacity	5 min	Measures bottleneck pressure
Facility operation data	Gate utilization	Ratio of actual gate flow to service capacity	5 min	Reflects ticket-checking pressure
Facility operation data	Waiting area occupancy	Proportion of occupied waiting space	5 min	Reflects space saturation
Train operation data	Arrival-departure intensity	Number of train arrivals/departures in each time interval	5 min	Captures operational concentration
Train operation data	Delay duration	Average deviation from scheduled train time	Event-based / 5 min	Captures disturbance effects
Train operation data	Inflow fluctuation amplitude	Short-term variation rate of passenger inflow	5 min	Reflects instability of demand

As shown in Table 1, the data design is fully consistent with the risk-analysis logic established in the previous section. Passenger monitoring variables indicate whether aggregation is already taking place, facility operation variables reveal whether the system is approaching its service limit, and train operation variables explain why the risk level may suddenly increase at a certain time. By combining these three data categories, the case study moves beyond a single-dimensional description of passenger volume and enables a more realistic representation of the dynamic evolution of passenger aggregation risk.

3.2 Early Warning Results

Based on the above data structure, passenger aggregation risk is dynamically evaluated over a representative peak period. Figure 2 illustrates the temporal evolution of the composite risk value. At the beginning of the observation period, the overall risk remains at a relatively low level, indicating stable operating conditions within the hub. As passenger inflow becomes more concentrated, the risk value gradually rises and enters a higher-risk range during the middle stage of the period. In particular, when train delay disturbances are superimposed on short-term passenger surges, the composite risk value increases sharply and approaches the critical warning level, suggesting that substantial queueing and localized crowding may already have emerged in key areas. After management interventions such as flow control and passenger guidance are introduced, the risk value declines and eventually returns to a relatively stable level.

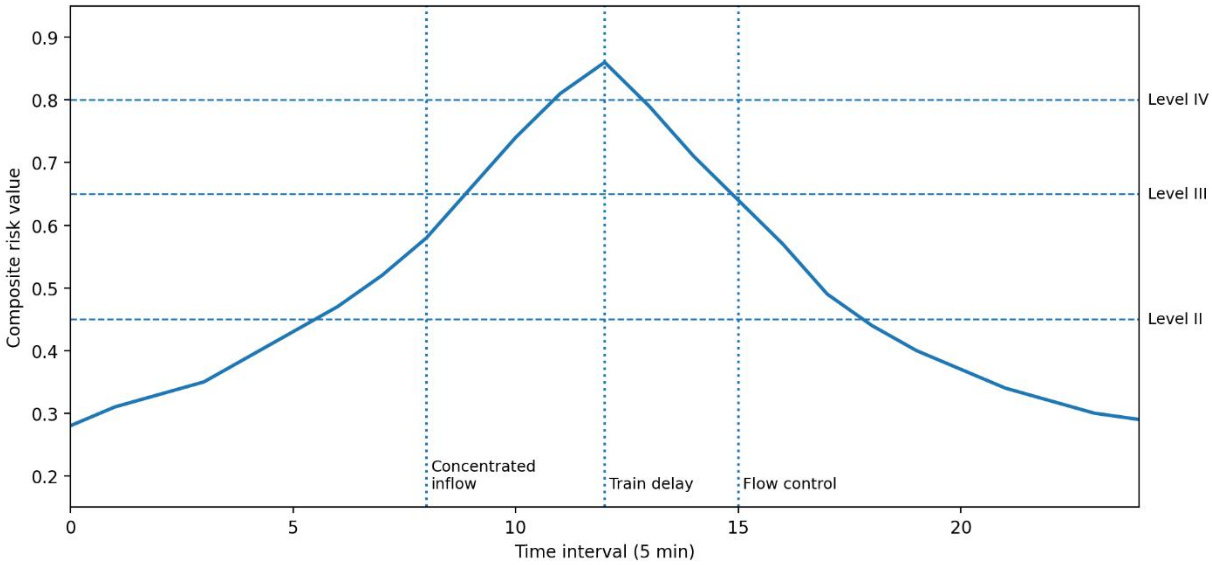

Figure 2 Evolution of Passenger Aggregation Risk

Figure 2 further indicates that the variation in risk is not random but clearly associated with operational events. The first significant increase corresponds to a period of concentrated passenger inflow, suggesting that demand-side shocks act as the direct trigger of aggregation risk. The second sharp increase is associated with a train delay event, indicating that operational disturbances can substantially amplify the existing pressure of passenger accumulation. Finally, the decline in the risk curve following management intervention suggests that the proposed dynamic warning framework is able not only to identify risk escalation but also to provide an actionable time window for operational response. In this sense, the framework effectively captures the full process of risk formation, escalation, and mitigation.

To further reveal the spatial characteristics of the warning results, Figure 3 presents the warning grades of different functional areas over successive time intervals. The results show that the security check area, waiting hall, and ticket gates are the most risk-sensitive locations and experience longer periods of elevated warning levels. Among them, the security check area and the ticket gates enter high-warning states earlier than the other areas, indicating that bottleneck facilities play a crucial role in amplifying system-wide aggregation risk. By contrast, the entrance hall and platform exhibit relatively smoother warning transitions, implying that their risk status is influenced more by upstream propagation than by intrinsic facility insufficiency.

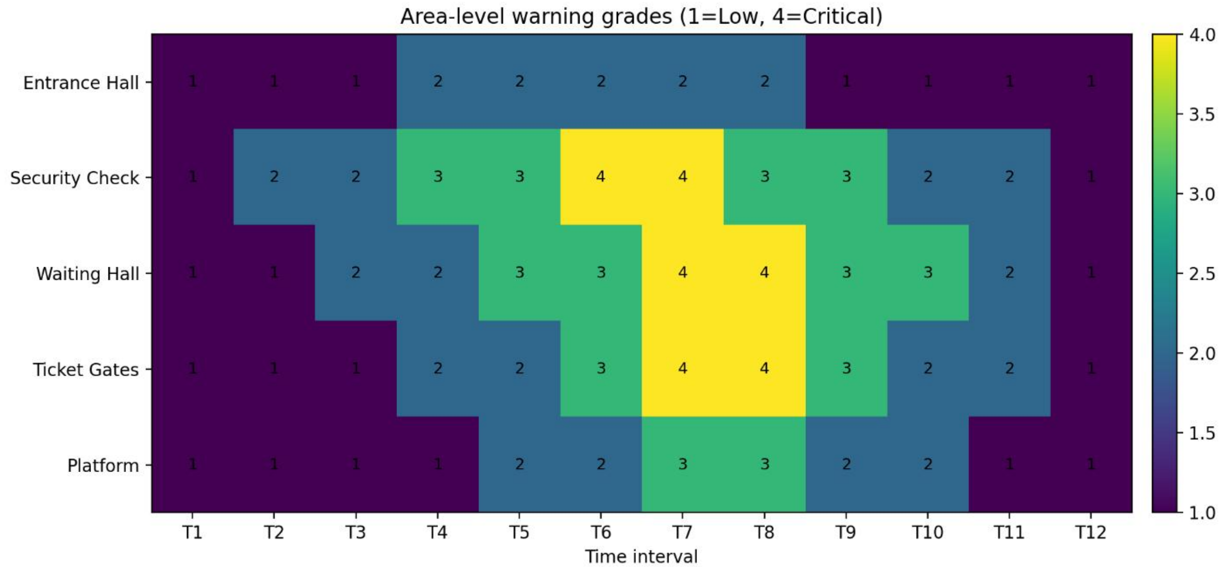

Figure 3 Area-Level Warning Grades over Time

Figure 3 also demonstrates the clear propagation feature of passenger aggregation risk in railway passenger hubs. High warning levels do not appear simultaneously in all areas; instead, they spread progressively along the passenger movement chain. In the illustrative case, the security check area first enters a high warning level, after which the elevated risk propagates to the waiting hall and ticket gates and ultimately affects the platform area. This observation is fully consistent with the mechanism analysis in Section 2 and further confirms that passenger aggregation risk in railway passenger hubs cannot be adequately understood from the state of a single area alone. Rather, it should be analyzed from the perspective of multi-area linkage and spatiotemporal evolution.

3.3 Result Analysis and Discussion of Warning Performance

To provide a more interpretable evaluation of the case results, Table 2 summarizes the main operating states and warning outcomes for each functional area. It can be observed that the security check area and ticket gates exhibit the highest average density, longest queue lengths, and greatest facility load ratios, and they also reach the highest warning levels. The waiting hall, although slightly lower in density than the security check area, still presents a prominent risk profile because of sustained passenger occupancy and delayed release. In contrast, the entrance hall and platform remain relatively stable in terms of both operating state and warning grade, suggesting that their risk status is mainly driven by upstream transmission rather than by local capacity limitations.

Table 2 Area-level Operating States and Warning Results

Area	Avg. density (person/m²)	Avg. speed (m/s)	Avg. queue length (person)	Avg. facility load ratio	Peak warning level	Main risk feature
Entrance Hall	0.82	1.10	18	0.54	II	Short-term inflow fluctuation
Security Check	1.96	0.63	74	0.91	IV	Strong bottleneck and queue accumulation
Waiting Hall	1.42	0.78	39	0.84	IV	Sustained occupancy and delayed release
Ticket Gates	1.71	0.66	58	0.88	IV	Concentrated boarding pressure
Platform	1.08	0.89	22	0.67	III	Downstream propagation from gates

When Table 2 is interpreted together with Figure 3, an important conclusion emerges: high-risk areas largely coincide with highly loaded facilities, which confirms that service-capacity constraints constitute a major endogenous driver of passenger aggregation risk. At the same time, although density and speed are useful for describing local crowd conditions, they are insufficient on their own to fully characterize risk. Without complementary variables such as queue length, facility utilization, and operational disturbances, the warning result would remain incomplete. This supports the necessity of the multi-indicator warning strategy adopted in this study, which provides a more comprehensive and operationally meaningful assessment of passenger aggregation risk.

From the perspective of warning performance, the case results suggest three notable strengths of the proposed framework. First, the warning results exhibit strong temporal sensitivity, as the rising trend of risk can be identified before the system reaches its most critical condition. Second, the framework provides high spatial resolution, allowing different functional areas to be distinguished in terms of warning level during the same period. Third, the warning results have clear managerial interpretability, because the dynamic risk process is translated into graded warning information that can directly support operational decisions. These features indicate that the framework is suitable not only for risk identification but also for decision support in on-site passenger organization, localized flow restriction, and emergency intervention at railway passenger hubs.

Overall, the case study demonstrates the applicability of the proposed dynamic early warning framework to the identification of passenger aggregation risk in railway passenger hubs. Although the figures and tables presented in this section are still illustrative rather than based on actual field data, the analytical logic clearly shows that passenger aggregation risk is not a static, isolated, or single-area problem. Instead, it is a dynamic process driven by multiple factors, evolving over time and propagating across space. A dynamic early warning framework that explicitly accounts for key-area interactions therefore provides a more suitable basis for practical risk identification and operational control.

4 DISCUSSION

The case results indicate that passenger aggregation risk at railway passenger hubs is not determined by passenger volume alone, but rather emerges as a dynamic process jointly driven by demand shocks, facility capacity constraints, and operational disturbances. As shown in Figure 2, the evolution of the composite risk value corresponds closely to periods of concentrated passenger entry, train delays, and subsequent management intervention. Figure 3 further demonstrates that high warning levels do not appear simultaneously across all areas, but instead propagate gradually along the passenger movement chain. These findings suggest that passenger aggregation risk in railway passenger hubs is characterized by clear time-varying, spatially heterogeneous, and propagative features. Therefore, static thresholds or judgments based on the condition of a single area are often insufficient for accurately capturing the actual risk level. By contrast, the dynamic early warning framework proposed in this study incorporates both multi-source information and inter-area linkage, making it more consistent with the real operating characteristics of railway passenger hubs.

From a methodological perspective, this study further confirms that passenger flow prediction is not equivalent to risk early warning. Much of the existing literature focuses primarily on the predictive accuracy of passenger volume, density, or crowding states, while relatively less attention has been paid to how these operational states can be transformed into risk information with direct management significance. By introducing a composite risk value and a graded warning mechanism, this study integrates passenger-state indicators, facility-load indicators, and disturbance factors into a unified analytical framework. As a result, risk identification is no longer limited to describing whether crowding is present; instead, it addresses more practically meaningful questions, such as what warning level the system is in, when the risk is escalating, and in which area the risk first emerges. In this sense, the contribution of this study lies not only in proposing a dynamic warning framework, but also in advancing a research perspective that moves from state recognition toward risk-oriented decision support for passenger safety management at railway passenger hubs.

From a practical point of view, the proposed framework has strong managerial interpretability and engineering applicability. First, the warning results are expressed in graded levels, which allows on-site operators to quickly understand the severity of the risk and adopt corresponding control measures. Second, the framework is able to distinguish the risk states of different functional areas within the same time period, which is particularly valuable for the refined management of key areas such as security checkpoints, ticket gates, waiting halls, and platforms. Third, because the framework emphasizes dynamic updating and inter-area propagation, it is applicable not only to routine peak-hour monitoring but also to disturbance scenarios such as train delays and short-term passenger surges. In other words, the framework is suitable for both normal operational management and emergency-oriented decision support.

Nevertheless, several limitations should be acknowledged. First, the current case analysis remains primarily illustrative, and further validation based on real monitoring data from railway passenger hubs is still needed, especially for parameter calibration, threshold setting, and warning-performance evaluation. Second, limited attention has been given to passenger behavioral heterogeneity, group psychology, and individual response differences, although these factors may play an important role in the evolution of aggregation risk under high-density conditions. Third, the present framework is mainly designed for risk identification within key areas of a single hub and has not yet been extended to more complex scenarios such as multi-hub interaction, intermodal transfer systems, or risk propagation across larger transportation networks. Future work may therefore focus on real-data-driven calibration, the incorporation of behavioral mechanisms, and integration with digital twin platforms, so as to improve both the generalizability and practical depth of the proposed model.

5 CONCLUSION

This study focused on the dynamic identification and early warning of passenger aggregation risk at railway passenger hubs and developed a warning-oriented analytical framework for key functional areas. Starting from the passenger handling process of railway passenger hubs, the study first examined the basis of risk formation and identified representative indicators from three dimensions, namely passenger-state conditions, facility operations, and operational disturbances. On this basis, a dynamic early warning framework was established, consisting of data input, state identification, risk assessment, and warning output. An illustrative case study was then used to demonstrate the application process of the proposed framework.

The results indicate that passenger aggregation risk at railway passenger hubs is characterized by strong dynamic variability and inter-area dependence. The risk level evolves continuously with changes in passenger inflow, facility load, and train operating conditions, while different functional areas exhibit differentiated warning states within the same period. In particular, critical nodes such as security checkpoints and ticket gates show higher sensitivity and stronger amplification effects during risk evolution, making them primary targets for warning and operational intervention. The case analysis further demonstrates that the proposed framework is capable of representing the risk evolution process and translating it into graded warning results with direct managerial relevance.

Overall, this study provides a structured analytical perspective for the identification and warning of passenger aggregation risk at railway passenger hubs, and offers methodological support for passenger safety management and operational optimization. Future research may build on real monitoring data to further validate threshold settings, parameter calibration, and cross-scenario applicability. It may also incorporate finer-grained behavioral information and real-time sensing technologies to improve the accuracy and practical usability of dynamic early warning models.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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