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REVIEW ARTICLE

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# Urban rail transit disruption management: Research progress and future directions

**Abstract** Urban rail transit (URT) disruptions present considerable challenges due to several factors: i) a high probability of occurrence, arising from facility failures, disasters, and vandalism; ii) substantial negative effects, notably the delay of numerous passengers; iii) an escalating frequency, attributable to the gradual aging of facilities; and iv) severe penalties, including substantial fines for abnormal operation. This article systematically reviews URT disruption management literature from the past decade, categorizing it into pre-disruption and post-disruption measures. The pre-disruption research focuses on reducing the effects of disruptions through network analysis, passenger behavior analysis, resource allocation for protection and backup, and enhancing system resilience. Conversely, post-disruption research concentrates on restoring normal operations through train rescheduling and bus bridging services. The review reveals that while post-disruption strategies are thoroughly explored, pre-disruption research is predominantly analytical, with a scarcity of practical pre-emptive solutions. Moreover, future research should focus more on increasing the interchangeability of transport modes, reinforcing redundancy relationships between URT lines, and innovating post-disruption strategies.

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**Keywords** urban rail transit, disruption management, resilient network, train rescheduling, bus bridging services

## 1 Introduction

Urban Rail Transit (URT) offers advantages such as energy efficiency, high capacity, and dependable all-weather operation. It plays a pivotal role in the endeavors of numerous major and medium-sized cities to alleviate traffic congestion. While URT offers passengers substantial travel convenience, it also confronts various operational challenges, including service delays and disruptions stemming from infrastructure degradation, facility malfunctions, track intrusions, medical emergencies, extreme weather conditions, and rolling stock failures (Pender et al., 2012). In July 2017, trash on the tracks ignited a fire at New York City's 145th street station, leading to significant delays and disruptions across multiple subway lines. The incident resulted in nine minor injuries, primarily due to smoke inhalation. More recently, in August 2022, a suicide attempt on the tracks caused a one-hour delay on Beijing Metro Line 2. Even the Hong Kong Metro, boasting a 99.9% on-time performance rate, encounters over 250 disruptions annually. Among these disruptions, 10% result in delays exceeding 30 min (Zhang and Lo, 2018; 2020).

These disruptions pose severe threats to the URT system for several reasons. i) High probability: URT is an extensive and complex system, featuring numerous signals, tracks, tunnels, and stations spanning a vast network. Complex transfer interactions exist between lines, leading to a high probability of URT disruption. Even a minor disruption in one component can reverberate through the entire network (Tan et al., 2020). ii) Significant negative consequences: Given the substantial passenger demand that URT accommodates, service disruptions can impact a large number of passengers. Delays result in passenger dissatisfaction and consequently have serious adverse societal consequences (Zheng et al., 2022). iii) Increasing frequency: As rail infrastructures age, the frequency of technical issues and subsequent service disruptions tends to rise (Currie and Muir, 2017). And iv) Stringent penalties: In some cities, URT operators face substantial financial penalties for service disruptions, creating significant financial burdens.

Therefore, effective disruption management is crucial to ensure the smooth and reliable operation of URT systems. Scholars increasingly focus on disruption management as a pressing concern. This article offers an in-depth review of the literature on URT disruption management from the past decade, examining it from two perspectives: Pre-disruption (pre-emptive) planning and post-disruption (reactive) measures, as illustrated in Fig. 1.

Pre-disruption planning includes actions undertaken prior to disruptions, with a primary focus on disruption prevention. Through comprehensive qualitative and quantitative analyses of network characteristics and passenger demand, it becomes possible to derive insights into the effect of disruptions on both the URT system and its passengers. These analyses also shed light on the propagation patterns of disruptions within the network and how passenger behavior evolves in response to disruptions (Li et al., 2020b). Armed with these insights, operators can strategically allocate protective resources and position standby equipment in areas most susceptible to disruptions or where disruption consequences would be most pronounced. Furthermore, by incorporating considerations of potential disruptions and route redundancy during the URT system's design phase, a highly resilient network can be constructed, thereby reducing delays and losses resulting from unforeseen disruptions and ensuring smoother operations.

Post-disruption measures include actions taken in the aftermath of disruptions, aimed at passenger evacuation and swift restoration of service to expedite the URT system's recovery. Currently, the most extensively researched and adopted post-disruption measures involve the adjustment of train schedules for disrupted lines and the provision of bus bridging services in impacted areas (Pender et al., 2012). Scholars have devised tailored train rescheduling plans that integrate various adjustment strategies to address different types of disruptions. Research on bus bridging services investigates areas such as route design, bus dispatching, and bus depot layout to explore more effective and efficient strategies.

The impact of disruptions on the URT system can be conceptualized as the configuration of a bathtub, as illustrated in Fig. 2 (Ghaemi et al., 2017). The black line shows the alteration in service quality when no disruption management measures are implemented. Upon the onset of a disruption, service quality precipitously deteriorates, persisting at a diminished level until the disruption or failure is rectified (Wang et al., 2021b). Pre-disruption planning is executed proactively before a disruption occurs, with the objective of diminishing the likelihood of disruptions or mitigating their effect on the system. Conversely, post-disruption measures aim to restore service to the greatest extent feasible following disruptions. The formulation of post-disruption measures relies on the analysis conducted in the pre-disruption phase, and conversely, well-designed post-disruption measures can enhance network resilience. When combined, these elements constitute a comprehensive strategy to ensure the safety, efficiency, and dependability of URT operations.

The structure of this article is as follows. Section 2 offers a literature review on pre-disruption planning, while Section 3 presents a review of the literature on post-disruption measures. Section 4 reviews the research combined pre-disruption and post-disruption. The results of this review are deliberated upon, and recommendations for further research are provided in Section 5.

## 2 Pre-disruption planning

Pre-disruption planning mitigates the effect of disruptions on the system and empowers URT operators to respond to disruptions with greater promptness and effectiveness.

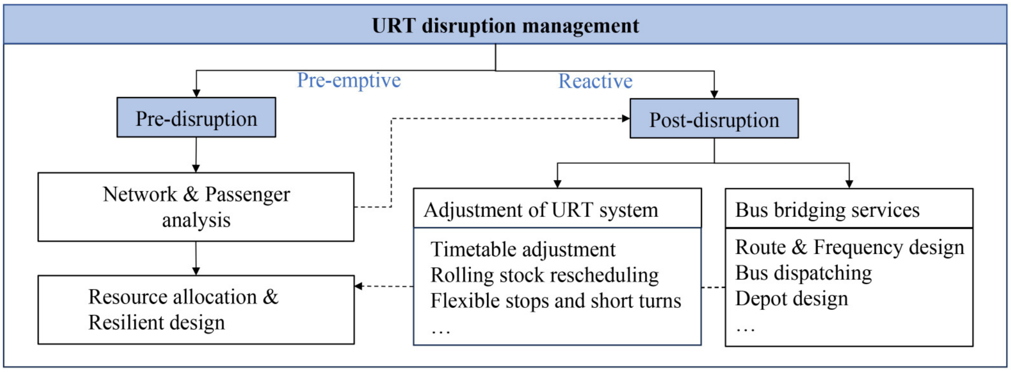

**Fig. 1** Structure of review.

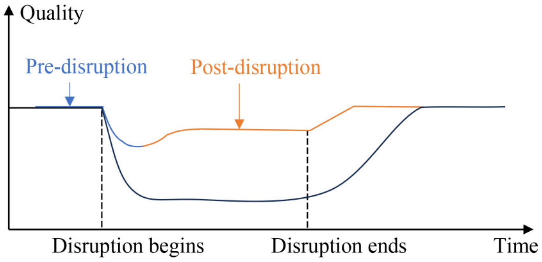

**Fig. 2** The effect of pre- and post-disruption measures.

A fundamental prerequisite for devising a successful pre-disruption plan is a comprehensive comprehension of the repercussions of disruptions on the URT system and the subsequent alterations in passenger behavior.

## 2.1 Network analysis

Due to the inherent interconnectedness and interdependence of URT networks, service disruptions at one or a few stations can reverberate throughout the entire line or even the entire network. Consequently, scientific network analysis assumes primary importance, with research in this domain primarily focusing on vulnerability analysis and resilience analysis (Chen et al., 2023).

Vulnerability pertains to the susceptibility to potential harm or disruption (Hong et al., 2022). Vulnerable components are those most liable to disruptions or those significantly adversely affected by them (De-Los-Santos et al., 2012). Krishnakumari et al. (2020) investigated passenger trajectories and dissected passenger delays into distinct categories, including track segment delay, initial waiting time, and transfer delay. This analysis aimed to discern the contributions of individual URT system components (e.g., stations and track segments) to overall passenger delays, thereby identifying vulnerable components warranting special attention. Zhang et al. (2021a) introduced four empirical vulnerability metrics founded on disruptions' effects on travel demand, average travel speed, and passenger flow distribution. These metrics facilitate the assessment of vulnerability for various stations within URT systems. Kopsidas and Kepaptsoglou (2022) devised a methodology for evaluating the criticality of URT stations through complex network analysis, considering alternative services during disruptions to determine which key stations necessitate prioritized protection. The methodologies proposed in the aforementioned literature aim to pinpoint vulnerable components necessitating pre-emptive protecting, thereby guiding subsequent resource allocation decisions and providing operators with decision-making insights.

Resilience denotes a system's ability to withstand and adapt to damage while swiftly recovering from a disrupted state (Chen et al., 2023). A highly resilient URT system can withstand external disruptions without substantial performance degradation and can promptly return to normal operation. In a well-developed URT network, certain lines can serve as alternatives to each other, affording passengers multiple routes to complete their journeys. This redundancy in routing assists the system in maintaining service capabilities during disruptions, thereby enhancing the overall resilience of the network. Xu et al. (2018) proposed a computational approach for assessing network redundancy, addressing fundamental questions concerning the effective redundant options available to passengers during normal or disruptive events and the extent of redundancy capacity within the network. Jing et al. (2020) introduced a method grounded in the concept of route redundancy for identifying critical stations within URT systems, introducing the mean-excess criticality probability as a risk metric for gauging the criticality of each station. Their findings suggest that key stations may not necessarily be transfer hubs, and stations pivotal for interval management, passenger flow, and network efficiency may not necessarily be key in terms of redundancy. Xu and Chopra (2022) adopted a resilience cycle framework, evaluating four phases tied to disruptions: Preparedness, robustness, recoverability, and adaptability. They proposed traffic weighting and spatial analyses as tools for assessing system and user resilience. Their conclusions highlight the advantage of densely constructed stations during recovery phases and underscore the pivotal role of route redundancy in enhancing resilience. Resilience analysis leans toward offering recommendations for response measures and network structure design from a forward-looking perspective, thereby facilitating the creation of a highly resilient and rapidly recovering network structure.

## 2.2 Passenger behavior/demand

Passengers play a dual role in the operation of URT systems, serving as integral participants and being directly affected by disruptions. Therefore, effective disruption management necessitates a consideration of their experiences.

On one hand, a segment of the literature quantifies the repercussions of disruptions on passengers. Sun et al. (2016) underscored the significance of comprehending how disruptions influence travel time, delays, and their ripple effects across stations and lines. Liu et al. (2021a) conducted simulations of accidents, investigating the propagation of passenger losses while accounting for both direct and indirect losses incurred through transfers between different lines. Eltved et al. (2021) introduced a novel methodology employing smart card data to investigate the long-term effects of disruptions on passengers.

On the other hand, the literature also endeavors to grasp passenger behavior during disruptions, capturing trends in shifting demands. Some passengers may opt to remain within the URT system, while others may seek alternative modes of transportation or even cancel their trips (Sun et al., 2016). Wang et al. (2014) established models for affected passengers employing a composite Poisson process, distinguishing between those who entirely abandon the service and those who discontinue their journey midway. Currie and Muir (2017) conducted an online survey of passenger responses to disruptions in Melbourne, revealing that a majority of passengers would be amenable to transitioning to rail replacement bus services. Pnevmatikou et al. (2015) utilized nested Logit models for a comprehensive analysis of revealed/stated preference data to examine alterations in passenger travel behavior. Li et al. (2020a) also developed a nested Logit model, consisting of two layers: The upper level representing mode shift choices and the lower level reflecting travel plan choices corresponding to mode shifts or the status quo. The findings underscore the significance of disruption characteristics and passengers' personal attributes as influential factors in mode shift decisions. Liu et al. (2021b) leveraged automatic fare collection data for a comprehensive analysis of the repercussions of unplanned disruptions. They formulated performance metrics and proposed inference methods to quantify individual responses, revealing that disruptions wield a network-wide influence and can have prolonged effects on passengers following the event. This underscores the significance of real-time information dissemination and timely updates.

### 2.3 Resources allocation

Building upon network and passenger demand/behavior analyses, some studies have undertaken more detailed investigations into the development of precise and pragmatic pre-disruption plans. Notably, subsequent to identifying vulnerable segments, scholars have explored methods to optimize the allocation of protective resources.

An et al. (2013) devised a model for establishing reliable emergency facility locations. Through an examination of the availability of evacuation resources, they determined an optimal strategy that strikes a balance between the efficiency of evacuees and operational costs. Jin et al. (2015) concentrated on scenarios where deliberate attacks trigger URT disruptions. They formulated a three-level game theory model including defenders, attackers, and users, yielding pre-emptive resource allocation strategies.

Another effective approach to managing disruptions involves proactively increasing the route redundancy within the urban transportation system. This ensures that passengers have a range of alternative modes available to complete their journeys, irrespective of whether a URT disruption has occurred (Hua and Ong, 2017). Jin et al. (2014) advocated for the integration of bus resources from a pre-disruption perspective to enhance the existing URT system. They developed a mathematical modeling framework to identify the optimal metro–bus integration solution. Yang et al. (2017) proposed a composite strategy combing passenger flow control with bus bridging services to alleviate congestion in the URT system during peak hours, similar to the oversaturated conditions experienced immediately after a disruption.

### 2.4 Resilient network design

A resilient URT network is essential to ensure consistent high-quality system operation. Nevertheless, it is challenging to fully anticipate service degradation and shifts in passenger demand resulting from disruptions during the initial design phase. This may lead to current optimal location decisions not performing well in dealing with future disruptions (Cadarso et al., 2017; 2018). Considering potential uncertainties and constructing a resilient network offer a more forward-looking perspective to mitigate the effect of disruptions.

While there is a dearth of studies specifically focused on designing networks for disruption scenarios, network designs that account for demand uncertainty remain valuable (Canca et al., 2019). Moccia et al. (2017) operated under the assumption of demand resilience and introduced a stochastic optimization model for bus route design, aiming to maximize operator profit and social welfare. Cadarso et al. (2017) presented a model for designing a rapid transit network, taking into consideration network reliability from the standpoint of recovery robustness and risk theory. Cadarso et al. (2018) extended their work by factoring in both passenger demand uncertainty and disruption occurrences of infrastructure elements within the network over a temporal horizon. They proposed a modeling approach for determining the sequence of investments in these network elements over time, departing from a single time period-based network design. Wang et al. (2023a) investigated new line design within an existing metro network, developing a robust optimization model that incorporates demand uncertainty. A comparison between the robust model and one that disregards uncertainty demonstrates that, especially in the case of large reductions in demand, which are similar to changes in demand after a long period of disruption, the robust design solution is more stable and competitive.

Furthermore, a deliberate effort to craft a URT network structure with a high degree of substitutability between lines during the design phase can enhance resilience. Passengers can still reach their destinations by transferring to alternative URT lines in the event of a partial disruption on their initial route. While there is literature on road network design that considers enhancing route redundancy from a traveler's perspective (Xu et al., 2021b; Zhu et al., 2023), no studies have specifically proposed network design solutions to bolster route redundancy between URT lines in preparation for future disruptions.

## 3 Post-disruption measures

In present operational scenarios, when an unplanned disruption occurs, operators are primarily tasked with expeditiously evacuating passengers and promptly restoring partial services. Two principal post-disruption measures are routinely implemented: Adjusting train schedules for the disrupted lines and deploying emergency bus bridging services.

### 3.1 Train rescheduling

Train rescheduling includes various actions, including timetable adjustments, rolling stock rearranging, intersection adaptations, route reconfiguration, flexible stopping strategies, and train capacity adjustments (Cacchiani et al., 2014). For instance, in November 2021, a section of Shanghai Metro Line 1, stretching from Lianhua Road Station to Shanghai South Railway Station, faced an unforeseen overhead line incident. In response, Line 1 was reconfigured to operate on a shorter route, running from Xujiahui Station to Fujin Road Station. Concurrently, a single-line, bi-directional operation was implemented between Xinzhuang Station and Xujiahui Station. Research efforts have also revolved around these operational strategies.

### 3.1.1 URT train rescheduling

Train rescheduling stands as the initial response undertaken by URT operators in the event of a disruption, thus warranting extensive research, with several studies integrating passenger characteristics into this domain. Cadarso et al. (2013) devised an integrated optimization model addressing the train timetable and rolling stock scheduling problem, accounting for disruptions' effect on passenger demand. They proposed a two-step framework, amalgamating the optimization model with a passenger behavior model. Building upon this foundation, Cadarso and Marín (2014) incorporated origin–destination demand to capture passenger path choices and mode shifts. They introduced an integrated timetable and rolling stock rescheduling model, aiming to minimize recovery time, passenger inconvenience, and adjustment costs. Besinovic et al. (2019) integrated the train rescheduling problem with a model for re-routing passengers according to a disrupted timetable and controlling station gates. Wang et al. (2018) amalgamated time-varying passenger flows into the timetable and rolling stock rescheduling problem. They introduced the iterative nonlinear programming (INP) method to address the multi-objective mixed-integer nonlinear programming challenge. Huang et al. (2020) investigated dynamic passenger flows and introduced nonlinear mixed-integer programming models including two recovery strategies: Alternating train directions and permitting short turns for train rescheduling during disruptions. To enable real-time model solving, a hybrid approach combining the large M and time-indexed formulation was proposed for model linearization, along with a two-stage approach to accommodate real-time information.

Several scholars have investigated train rescheduling for disruptions of varying sizes, durations, and locations. Cadarso et al. (2015) addressed large-scale disruptions by devising an integrated model for timetables and rolling stock rescheduling. Their model not only aims to develop rescheduling solutions in terms of service quality and operating costs but also keeps practical implementation feasibility in mind. Xu et al. (2016) established a rescheduling model to address incidents on dual-track subway lines, particularly focusing on a crossover track connecting two parallel URT lines. Their objective was to find a near-optimal rescheduling timetable that minimizes total delay time compared to the original schedule. Wang et al. (2021b) investigated real-time timetable and rolling stock scheduling problems arising from complete blockages of URT lines. They formulated a complex multi-objective mixed-integer linear programming (MILP) model that considers timetable deviations, (partial) cancellations, and headway deviations. A two-stage methodology characterized by high computational efficiency was introduced to address the model in real-time. In the first stage, a smaller-scale optimization problem, concentrating on a set of pivotal rotation stations, was resolved. Subsequently, in the second stage, adjustments to variables in the original MILP problem were made, informed by the solution derived from the first stage.

Minor disruptions and disturbances are commonplace in URT operations. Due to limited scheduling flexibility and high-frequency train services, even minor disruptions lasting 10 min can easily propagate to other trains or lines, significantly impairing service quality. Gao et al. (2017) proposed a strategy for real-time automatic schedule rescheduling with integrated fault dynamics processing for minor faults in URT operations. Real-time train adjustments are essential for disturbances. Chen et al. (2022) explored dynamic train regulation and stop-skipping strategies to address frequent disturbances in real-time. They developed a nonlinear programming model for dynamic passenger flow with the objective of minimizing total train deviation and enhancing passenger service quality, further converting it into a mixed-integer quadratic programming model. A customized model predictive control (MPC) approach was provided, enabling real-time model solving. Jin et al. (2022) introduced a real-time train regulation method that considers substation peak power reduction while minimizing headway deviations and avoiding multiple trains' acceleration by adjusting running time and dwell time. The MPC method was employed to meet real-time requirements.

The above literature is summarized in Table 1.

**Table 1** Summary of relevant studies on train rescheduling for URT systems

| Literature | Strategy | Special consideration | Objective | Algorithm |
|---|---|---|---|---|
| Cadarso et al. (2013) | ST, ET, CA, TO, CC | Passenger behavior | OC, CA, PD, AD | CPLEX |
| Cadarso and Marín (2014) | RT, ET, CA, RS | Passenger path choices and mode shifts | TD, PI, AD | CPLEX |
| Cadarso et al. (2015) | RT, CA, ET, CC | Large-scale disruptions | AD, OQ | CPLEX |
| Xu et al. (2016) | RT, TO | Incidents on dual-track lines | TD | Efficient train rescheduling strategy (ETRS); COIN-CBC |
| Gao et al. (2017) | RT | Minor faults | AD | Simulation system; GUROBI |
| Wang et al. (2018) | RT, RS | Dynamic passengers | AD | INP methods; CPLEX |
| Huang et al. (2020) | TO, ST | Dynamic passengers | PI, AD | Two-stage approach; CPLEX |
| Besinovic et al. (2019) | RT, ST, RR, CA | Controlling passenger flows | PD, PI, AD, TD | GUROBI; Sequential quadratic programming (SQP) algorithm |
| Wang et al. (2021b) | RT, CA, ST, RS | Complete blockage | AD, CA | Two-stage approach; CPLEX |
| Chen et al. (2022) | SP | Disturbances; Dynamic passengers | AD, OQ | MPC; GUROBI |
| Jin et al. (2022) | RT | Disturbances; Peak power reduction | AD | MPC; CPLEX |

Notes: ST: short turns, ET: emergency train, CA: cancelling, TO: two-way traffic on a single track, CC: composition change, RT: re-timing, RS: rolling stock, RR: re-routing, SP: stopping patterns adjustments (skipping and adding stops); OC: operational cost, PD: passenger delays/travel cost, AD: adjustments deviations, TD: train delays, PI: passenger inconvenience, OQ: operational quality.

### 3.1.2 Railway rescheduling

URT, including subway, light rail, surface railroads, monorails, streetcars, maglev trains, and automated guided rail systems, exhibits diverse infrastructure arrangements. Subways tend to be prominent in the central districts of densely populated metropolises, while surface railroads, light rail systems, and the like are commonly found in suburban areas. In light of the similarities between URT and traditional railway systems, it is pertinent to consider the literature on traditional railway disruption management.

Traditional railways, characterized by lower operational frequency and greater track flexibility, generally offer more adaptable options, especially in regions with parallel lines and multiple switches. Consequently, they can employ a wider range of strategies when disruptions occur. Louwerse and Huisman (2014) concentrated on timetable adjustments in the event of major disruptions, including both partial and complete blockages of railway lines. They explored optimal solutions involving rescheduling, reordering, canceling, and implementing short turns. Zhu and Goverde (2019) innovatively integrated multiple scheduling strategies, including rescheduling, reordering, cancelations, flexible stops (e.g., skipping and adding stops), and adaptable short turns, to formulate an efficient timetable and rolling stock rescheduling model. Subsequently, Zhu and Goverde (2020) considered station capacity and introduced a passenger-oriented rescheduling framework, amalgamating timetable adjustments and passenger reassignment into an MILP model. This model offers comprehensive scheduling strategies, such as train rescheduling, cancellations, flexible stops, and adaptable short turns. To facilitate efficient problem-solving, they introduced an Adaptive Fix-and-Optimize (AFaO) algorithm.

Recent research has investigated specific disruption scenarios. Zhu and Goverde (2021) devised another MILP model addressing situations involving multiple disruptions occurring concurrently but at distinct locations. Their study employed a space-time network-based model and introduced two methods for rescheduling timetables in dynamic environments: Sequential and combinatorial approaches, alongside a rolling horizon approach for multi-disruption scenarios. Zhan et al. (2021) investigated the problem of train rescheduling and passenger rerouting when trains cannot traverse disrupted segments. They formulated this problem as an integer linear programming (ILP) model based on a space-time network. Employing the Alternating Direction Method of Multipliers (ADMM), they decomposed the model into two sub-problems, which were further divided into a series of shortest-path problems for individual trains or passengers, solved through dynamic programming algorithms.

Railway operators make timetable and resource adjustments in response to disruptions. Concurrently, passengers adapt their routes based on personal preferences. Consequently, train adjustments are considered essential to accommodate changes in passenger behavior. Binder et al. (2017) proposed a passenger-oriented model to address the post-disruption train rescheduling and passenger assignment problem. Veelenturf et al. (2017) allowed passengers’ travel choices to exert slight modifications to the train schedule and enhanced service quality through careful adjustments to stopping patterns. van der Hurk et al. (2018) combined passenger route advice with rolling stock rescheduling in the face of uncertain disruption durations. They posited that passengers would receive route advice but might not necessarily adhere to it. Consequently, rolling stock would also be rescheduled based on the route advice to cater to anticipated demand.

The literature discussed above is summarized in Table 2.

Crew rescheduling is a critical facet of traditional railway disruption management. Typically, the timetable, rolling stock, and crew schedules are adjusted sequentially, but achieving more efficient adjustments through integration proves challenging due to the resulting problem's impractical size (Zhang et al., 2021b). Consequently, some literature has examined the crew rescheduling problem in isolation. For instance, Yuan et al. (2022b) introduced a depth-first search crew recovery method to address real-time crew rescheduling challenges effectively.

### 3.1.3 Mass evacuation

Research on passenger flow analysis (Li et al., 2020a) suggests that during brief and localized disruptions where partial services remain, a substantial number of passengers may still opt for URT, resulting in passenger accumulation within the affected segment. Gao et al. (2016) proposed the option of bypassing certain stations to expedite train circulation and promptly clear stranded passengers. Their study considered factors such as overcrowding and fluctuating passenger flow, presenting an optimization model including train rescheduling and stopping strategies. An iterative algorithm was devised for solving the decomposed model.

The characteristics of excessive crowding in passenger flow during peak hours bear similarities to passenger flow during disruptions. Therefore, research on train rescheduling during peak hours also offers valuable insights for disruption management. Niu and Zhou (2013) investigated timetable optimization under severe congestion, accounting for scenarios where passengers are unable to board the first train and must await the next one. They devised a binary integer optimization model grounded in dynamic passenger demand. Yuan et al. (2022a) aimed to enhance service frequency in high-demand areas during peak hours using a limited number of trains, thereby reducing total waiting times for platform passengers. They formulated a comprehensive optimization model including train schedules, rolling stock, and bidirectional URT line short-turn strategies. The model explicitly considered train capacity, turnaround times, and the available number of trains. A hybrid genetic algorithm was developed to yield high-quality solutions.

Furthermore, the transition from off-peak to peak periods witnesses substantial shifts in passenger demand, akin to the uneven distribution of passenger flows following a disruption. Research in this domain provides methodological guidance as well. Guo et al. (2017) specifically addressed timetable optimization during transition periods, employing a mixed-integer nonlinear programming model focused on maximizing transfer synchronization. They devised a hybrid algorithm combining Particle Swarm Optimization and Simulated Annealing to achieve near-optimal solutions. Zhou et al. (2022) introduced a joint optimization approach for timetable and rolling stock scheduling problems, tailored to periods of tidal oversaturated passenger demand. This method flexibly allocates trains with varying load capacities to match the imbalanced passenger flow.

## 3.2 Bus bridging service

The accumulation of disruption time has led to an increase in both the number of affected passengers and their delay minutes. Monsuur et al. (2021) observed that passengers responded negatively to delays exceeding 30 min. Consequently, for prolonged disruptions or those affecting a broad area, simply rescheduling the disrupted line often proves inadequate. In practical URT operations, emergency bus bridging services are deployed within the affected region to serve as an alternative to the degraded URT network.

**Table 2** Summary of relevant studies on train rescheduling for railway systems

| Literature | Strategy | Special consideration | Objective | Algorithm |
|---|---|---|---|---|
| Louwerse and Huisman (2014) | RT, RO, CA, ST | Major disruptions | TD, CA | CPLEX |
| Kroon et al. (2015) | RS | Dynamic passenger | OC | Iterative heuristic approach |
| Binder et al. (2017) | RT, RO, RR, ET, CA, SP | Major disruptions | OC, AD, PI | CPLEX; $\varepsilon$ constraints |
| Veelenturf et al. (2017) | SP, RS | Incomplete blockage; Passengers' free choice | OC, PD, AD | Iterative heuristic approach |
| van der Hurk et al. (2018) | RS | Major disruptions; Uncertain duration; Passengers' route advice | PI | Iterative algorithm |
| Zhu and Goverde (2019) | RT, RO, CA, SP, ST, RS | All phases of a disruption | PD | GUROBI |
| Zhu and Goverde (2020) | RT, RO, CA, SP, ST, RS | Station capacities | PD, PI | AFaO algorithm |
| Zhu and Goverde (2021) | RT, ST | Multiple disruptions occur simultaneously | CA, AD | Rolling horizon solution method |
| Zhan et al. (2021) | RT, CA, PR | Complete blockage | OC, PD | Two-layer decomposition; ADMM algorithm |

Notes: RT: re-timing, RO: re-ordering, CA: cancelling, ST: short turns, RS: rolling stock, RR: re-routing, ET: emergency train, SP: stopping patterns adjustments (skipping and adding stops), PR: passenger re-routing; TD: train delays, OC: operational cost, AD: adjustments deviations, PI: passenger inconvenience, PD: passenger delays/travel cost.

According to a study, even though it may take some time for the bus bridging service to become fully operational, over two-thirds of passengers will still opt for shuttle buses as long as bus services are scheduled (Currie and Muir, 2017). For instance, during the disruption on Shanghai Metro Line 1 in November 2021, the transportation department assigned 44 buses to operate between Xinzhuang Station and Xujiahui Station on Line 1. These buses provided bidirectional service between the two stations, making stops at each station along a path parallel to the disrupted section of the URT line, referred to as the "standard route". The bus bridging service remained in operation for 90 min, successfully evacuating nearly 4000 passengers. To further enhance the efficiency of bus bridging services, researchers are exploring various aspects such as bus dispatching, bus route design, and frequency planning.

#### 3.2.1 Route and frequency design

In the domain of designing bus routes and frequencies during disruptions, Wang et al. (2016) introduced a model for bus dispatching and the design of standard routes in emergency situations. The goal was to minimize the overall cost of the shuttle bus service. Recognizing that standard routes could lead to vehicle queues and congestion at terminal station berths, Dou et al. (2019) addressed this issue by considering the availability of parking spots. They divided a standard parallel shuttle route into multiple non-overlapping short bus routes.

Recent research has explored diverse routes to enhance the efficiency of bus bridging services. Gu et al. (2018) accounted for stations with high passenger flow, such as transfer stations, and devised express routes that allowed for the skipping of stops. Wang et al. (2019) factored in dynamic passenger flows during disruptions and developed a multi-objective optimization model for designing standard and express bus routes. The aim was to minimize the total waiting time, the number of stranded passengers, and the number of dispatched buses. Jin et al. (2016) proposed nonintuitive shuttle bus routes between disrupted stations and neighboring non-disrupted stations with high demand. This led to significant reductions in average passenger travel delays. Using a column-generation algorithm, they generated a set of candidate bridging bus routes and identified the most effective combinations of these routes and bus deployment based on a path-based multicommodity flow model. van der Hurk et al. (2016) designed both standard routes and interline nonintuitive routes. In contrast to Jin et al. (2016), they developed a path-based mixed-integer programming model to simultaneously determine the optimal set of bridging bus routes, frequencies, and bus deployment. Chen and An (2021) conducted a comprehensive study that integrated standard, short-turn, and express routes to serve passengers. Their work included an integrated optimization framework, employing a brute-force search method to identify all candidate routes, followed by an MILP model to address route selection, bus deployment, and timetable problems in the context of time-varying demand. Finally, a tabu search method was utilized to efficiently solve the model. Wang et al. (2023b) devised nonintuitive bridging routes between non-disrupted stations indirectly affected by the disruption but not located within the disruption zone itself. The design of the bus bridging service and passenger assignment problem was formulated as a path-based ILP model, which was efficiently solved by generating nonintuitive routes using a column generation-based approach. Figure 3 illustrates the various bridging bus routes suggested in the aforementioned literature.

URT service disruptions often occur suddenly and are of a temporary nature, introducing uncertainties in various aspects, such as the disruption's duration, the punctuality of shuttle buses, and passenger demand. Building upon the work of Jin et al. (2016), Liang et al. (2019) incorporated the uncertainty associated with bus travel times and devised a robust optimization framework, resulting in more stable solutions. Xu et al. (2021a) formulated a distributed robust optimization model that provided effective bus bridging services and station response strategies, accounting for uncertain disruption durations.

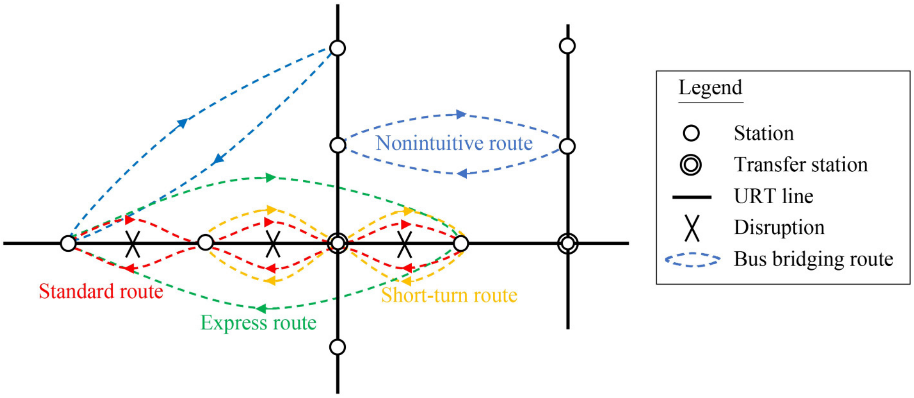

**Fig. 3** Bus bridging routes.

Taking into consideration both the reliability of the regular bus system and the uncertainty of passenger demand, Zheng et al. (2022) introduced two operational approaches: Fixed-stop shuttle services and demand-responsive services tailored to meet the diverse needs of passengers.

### 3.2.2 Bus dispatching

The availability of shuttle buses plays a pivotal role in determining the efficiency of bridging services during URT disruptions. URT operators often face challenges in dispatching shuttle buses rapidly and adequately due to constraints such as a shortage of available vehicles, road congestion, and cumbersome bus application procedures. Many existing studies operate under the assumption that vehicles are dispatched from bus depots (Wang et al., 2022). For instance, Wang et al. (2021a) introduced a bi-level optimization model for shuttle bus timetabling and dispatching. This model considers transfer passenger flows and incorporates the concept of passenger tolerance to determine successful transfers. The upper level focuses on timetable optimization, aiming to minimize passenger waiting times and missed transfers, while the lower level addresses vehicle dispatching with the goal of minimizing operational costs.

Given the substantial number of passengers affected by disruptions and the potential inadequacy of buses from depots, some researchers have explored alternative means of dispatching vehicles. Itani et al. (2020) considered dispatching buses from the terminals of neighboring bus lines when there were insufficient spare vehicles in depots. They developed an optimization model for bus dispatching with the objective of minimizing the total delay time for both URT and bus users. However, if the terminals are located far from the disrupted stations, the shuttle buses may take too long to arrive, hindering the swift evacuation of passengers. Taking this into further consideration, Wang et al. (2022) proposed expanding the sources of buses to include both spare vehicles from depots and regular buses currently operating near the disrupted area. They established an integer programming model to determine the optimal dispatching solution, and the results indicated that utilizing regular buses already in operation has significant potential to reduce passengers' delays.

### 3.2.3 Bus depots design

Several studies have investigated the design of dedicated bus depots specifically tailored for managing disruptions, thoroughly assessing their economic viability and location selection. Pender et al. (2014) introduced a novel concept for bus deployment: Satellite depots or virtual depots. These designated areas are established for parking buses that can be rapidly deployed to address unplanned disruptions and other unforeseen events. The study proposed a method for selecting optimal satellite depot locations, taking into account factors such as railway travel time, the frequency of disruptions, and the scale and spatial distribution of affected passengers. The objective is to facilitate a swift and precise response to the demand for bus bridging services. In a subsequent study, Pender et al. (2015) explored the economic feasibility of reserving buses exclusively for peak periods during disruptions. The findings indicated that bus reservation exhibits strong net economic benefits, and the investment rationale should be based on economic considerations rather than purely financial benefits, as the reserves constitute a net cost.

### 3.3 Multiple modes strategy for disruption

Scholars have also proposed leveraging various transportation modes to facilitate the evacuation of passengers in the aftermath of disruptions (Yin et al., 2018). Yang and Chen (2019) advocated for the use of ride-hailing services as an appealing option for evacuating stranded passengers and complementing bus bridging services. They formulated a service supply chain including vehicles, platforms, and passengers, and devised compensation strategies for online ride-hailing platforms within the disruption zone, employing a game-theoretic model. Tan et al. (2020) recommended enhancing passenger evacuation by increasing the frequency of regular bus services. Luo and Xu (2021) posited that the remaining capacity of operational URT and regular bus routes could be tapped to provide supplementary services. To this end, they designed an integrated network including the available rail lines, existing operational bus routes, and newly introduced shuttle bus routes.

## 4 Combination of pre-disruption and post-disruption measures

Current research concerning the combination of pre-disruption and post-disruption measures has primarily revolved around comparing network performance before and after disruptions. This evaluation of the effectiveness of post-disruption measures can also yield valuable insights for pre-disruption planning. Tessitore et al. (2022) conducted an assessment of train rescheduling strategies and provided guidance on promptly adjusting train schedules based on prevailing traffic conditions and the nature of the disruption. Liu et al. (2021b) evaluated network performance from the perspective of post-disruption shuttle bus services in their pre-disruption analysis. Tang et al. (2021) assessed the effectiveness of bus bridging services and the resilience of URT systems using a linear programming optimization model. Their findings indicated that bus bridging services can enhance system recovery capacity by 14% to 30%. Additionally, Li et al. (2023) introduced a resilience-oriented quantitative evaluation index for measuring system performance during disruptions and developed a train rescheduling model that considers the effect of station congestion to bolster system resilience. These findings offer recommendations for the capacity planning of key stations, particularly transfer stations. Nonetheless, the combination of pre-disruption and post-disruption perspectives in research remains relatively limited, as scholars often employ different methodologies for each phase, with the former emphasizing analysis and the latter focusing on optimizing models.

## 5 Discussion and future directions

This paper provides a comprehensive analysis of the literature on URT disruption management from the past decade, with a focus on methodologies, research objectives, and key findings. The research in this domain has been categorized into two primary areas based on the timing of the proposed measures: Pre-disruption planning and post-disruption measures.

Pre-disruption planning includes measures taken before disruptions occur to mitigate their adverse effects. Numerous studies have investigated this domain, involving analyses of the URT network to identify areas requiring reinforcement, investigations into passenger behavior and demand fluctuations following disruptions, the development of route redundancy and resource allocation strategies based on these analyses, and the design of highly resilient networks. In essence, pre-disruption planning revolves around understanding potential vulnerabilities, anticipating passenger behavior, devising strategies to address them, and designing systems with inherent resilience.

The research on post-disruption measures predominantly focuses on the two prevailing approaches to disruption management, namely train rescheduling and bus bridging services. In the context of the train rescheduling problem, various optimization models have been established to address different types of disruptions, employing diverse adjustment strategies such as timetable adjustments, train cancellations, short turns, and flexible stops. These models have been complemented by the development of efficient algorithms for their solution. Concerning the bus bridging design problem, scholars have devised unique optimization models to design efficient bus bridging routes for large-scale evacuations and have explored various bus resources to enable rapid response. To further enhance efficiency, the integration of various transportation modes, including taxis, ride-hailing services, regular buses, etc., has been suggested to increase evacuation capacity.

In recent literature, a novel approach has emerged that combines pre-disruption and post-disruption considerations. Researchers in this domain assess the effectiveness of post-disruption measures by quantifying network resilience both before and after disruptions, thereby offering valuable insights for pre-disruption planning.

In summary, the past decade has witnessed substantial research in the field of URT disruption management. The methodologies, models, algorithms, and case studies presented in these studies have proven instrumental in aiding operators in making informed decisions and generating fresh ideas for real-world disruption management. Nevertheless, it is worth noting that in some cities, URT networks have not been in operation for an extended period, such as regions in China, where the majority of URT systems have been constructed within the last two decades, and major disruptions have been infrequent. Consequently, not all the disruption management strategies proposed in recent research have been fully implemented. Many URT systems are yet to establish comprehensive pre-disruption planning systems, and the post-disruption measures currently employed often remain relatively basic, including direct train cancellations and bus bridging services with standard routes.

The forthcoming discussion addresses the challenges associated with URT disruption management and outlines potential avenues for future research.

First and foremost, proactive pre-disruption planning is essential for minimizing the adverse effects of unforeseen events and ensuring the continuity and resilience of URT systems. From the operator’s perspective, pre-disruption planning proves more effective than reactive post-disruption measures, particularly in terms of reducing passenger inconvenience and minimizing delays. While current research in pre-disruption planning predominantly revolves around network and behavior analyses, there exists a noticeable gap in studies that focus on the development of practical pre-emptive plans specifically tailored for disruption scenarios and feasible for real-world implementation. Future research endeavors could consider adding new regular bus routes near vulnerable sections of existing URT systems and enhancing redundancy between lines by optimizing transfer connections during the network design phase.

The challenge of evacuating passengers following a disruption remains a complex issue. Train rescheduling can only partially restore services on the disrupted line, and dispatching a sufficient number of buses for bridging services in a timely manner is often challenging. The two primary post-disruption measures currently in use may not always suffice to address evacuation needs, especially in the context of disruptions affecting high-density urban rail networks during peak hours. Therefore, researchers should explore innovative measures for rapid and extensive passenger evacuation. For instance, it is conceivable to optimize the utilization of capacity on other undisrupted

URT lines within the system to facilitate passenger evacuation, with mechanisms in place to adjust the frequency of these lines to accommodate increased passenger loads.

Additionally, disruptions that prompt a significant number of passengers to switch to alternative modes of transportation may have implications for road traffic. Nevertheless, research in this domain remains limited, including aspects such as the effect of disruptions on road traffic, the extent of this effect, and strategies to mitigate it. Collaborative road traffic management approaches can also be explored in the context of URT disruption management.

Lastly, optimization models have been widely employed for train adjustment and bus bridging services design, and researchers have made efforts to develop various algorithms for efficiently obtaining optimal solutions. The emergence of artificial intelligence presents new opportunities for rapidly solving large-scale models, which can play a pivotal role in future research on URT disruption management.

**Competing Interests** The authors declare that they have no competing interests.

## References

An S, Cui N, Li X, Ouyang Y (2013). Location planning for transit-based evacuation under the risk of service disruptions. Transportation Research Part B: Methodological, 54: 1–16

Besinovic N, Wang Y, Zhu S, Quaglietta E, Tang T, Goverde R M P (2019). Integrated train and passenger disruption management for urban railway lines. In: IEEE Intelligent Transportation Systems Conference (ITSC). Auckland: IEEE, 3182–3187

Binder S, Maknoon Y, Bierlaire M (2017). The multi-objective railway timetable rescheduling problem. Transportation Research Part C: Emerging Technologies, 78: 78–94

Cacchiani V, Huisman D, Kidd M, Kroon L, Toth P, Veelenturf L, Wagenaar J (2014). An overview of recovery models and algorithms for real-time railway rescheduling. Transportation Research Part B: Methodological, 63: 15–37

Cadarso L, Codina E, Escudero L F, Marín A (2017). Rapid transit network design: Considering recovery robustness and risk aversion measures. Transportation Research Procedia, 22: 255–264

Cadarso L, Escudero L F, Marín A (2018). On strategic multistage operational two-stage stochastic 0–1 optimization for the Rapid Transit Network Design problem. European Journal of Operational Research, 271(2): 577–593

Cadarso L, Marín Á (2014). Recovery of disruptions in rapid transit networks with origin–destination demand. Procedia: Social and Behavioral Sciences, 111: 528–537

Cadarso L, Marín Á, Maróti G (2013). Recovery of disruptions in rapid transit networks. Transportation Research Part E: Logistics and Transportation Review, 53: 15–33

Cadarso L, Maróti G, Marín Á (2015). Smooth and controlled recovery planning of disruptions in rapid transit networks. IEEE Transactions on Intelligent Transportation Systems, 16(4): 2192–2202

Canca D, De-Los-Santos A, Laporte G, Mesa J A (2019). Integrated railway rapid transit network design and line planning problem with maximum profit. Transportation Research Part E: Logistics and Transportation Review, 127: 1–30

Chen J, Jiang C, Liu X, Du B, Peng Q, Yin Y, Li B (2023). Resilience enhancement of an urban rail transit network by setting turn-back tracks: A scenario model approach. Transportation Research Record: Journal of the Transportation Research Board, in press, doi:10.1177/03611981231164066

Chen Y, An K (2021). Integrated optimization of bus bridging routes and timetables for rail disruptions. European Journal of Operational Research, 295(2): 484–498

Chen Z, Li S, D'Ariano A, Yang L (2022). Real-time optimization for train regulation and stop-skipping adjustment strategy of urban rail transit lines. Omega, 110: 102631

Currie G, Muir C (2017). Understanding passenger perceptions and behaviors during unplanned rail disruptions. Transportation Research Procedia, 25: 4392–4402

De-Los-Santos A, Laporte G, Mesa J A, Perea F (2012). Evaluating passenger robustness in a rail transit network. Transportation Research Part C: Emerging Technologies, 20(1): 34–46

Dou X, Wang H, Meng Q (2019). Parallel shuttle bus service design for planned mass rapid transit shutdown: The Singapore experience. Transportation Research Part C: Emerging Technologies, 108: 340–356

Eltved M, Breyer N, Ingvardson J B, Nielsen O A (2021). Impacts of long-term service disruptions on passenger travel behaviour: A smart card analysis from the Greater Copenhagen area. Transportation Research Part C: Emerging Technologies, 131: 103198

Gao Y, Kroon L, Schmidt M, Yang L (2016). Rescheduling a metro line in an over-crowded situation after disruptions. Transportation Research Part B: Methodological, 93: 425–449

Gao Y, Yang L, Gao Z (2017). Real-time automatic rescheduling strategy for an urban rail line by integrating the information of fault handling. Transportation Research Part C: Emerging Technologies, 81: 246–267

Ghaemi N, Cats O, Goverde R M P (2017). Railway disruption management challenges and possible solution directions. Public Transport, 9(1–2): 343–364

Gu W, Yu J, Ji Y, Zheng Y, Zhang H M (2018). Plan-based flexible bus bridging operation strategy. Transportation Research Part C: Emerging Technologies, 91: 209–229

Guo X, Sun H J, Wu J J, Jin J G, Zhou J, Gao Z Y (2017). Multi-period-based timetable optimization for metro transit networks.

Transportation Research Part B: Methodological, 96: 46–67

Hong W T, Clifton G, Nelson J D (2022). Rail transport system vulnerability analysis and policy implementation: Past progress and future directions. Transport Policy, 128: 299–308

Hua W, Ong G P (2017). Network survivability and recoverability in urban rail transit systems under disruption. IET Intelligent Transport Systems, 11(10): 641–648

Huang Y, Mannino C, Yang L, Tang T (2020). Coupling time-indexed and big-M formulations for real-time train scheduling during metro service disruptions. Transportation Research Part B: Methodological, 133: 38–61

Itani A, Srikukenthiran S, Shalaby A (2020). Capacity-constrained bus bridging optimization framework. Transportation Research Record: Journal of the Transportation Research Board, 2674(5): 600–612

Jin B, Feng X, Wang Q, Sun P (2022). Real-time train regulation method for metro lines with substation peak power reduction. Computers & Industrial Engineering, 168: 108113

Jin J G, Lu L, Sun L, Yin J (2015). Optimal allocation of protective resources in urban rail transit networks against intentional attacks. Transportation Research Part E: Logistics and Transportation Review, 84: 73–87

Jin J G, Tang L C, Sun L, Lee D H (2014). Enhancing metro network resilience via localized integration with bus services. Transportation Research Part E: Logistics and Transportation Review, 63: 17–30

Jin J G, Teo K M, Odoni A R (2016). Optimizing bus bridging services in response to disruptions of urban transit rail networks. Transportation Science, 50(3): 790–804

Jing W, Xu X, Pu Y (2020). Route redundancy-based approach to identify the critical stations in metro networks: A mean-excess probability measure. Reliability Engineering & System Safety, 204: 107204

Kopsidas A, Kepaptsoglou K (2022). Identification of critical stations in a metro system: A substitute complex network analysis. Physica A, 596: 127123

Krishnakumari P, Cats O, van Lint H (2020). Estimation of metro network passenger delay from individual trajectories. Transportation Research Part C: Emerging Technologies, 117: 102704

Kroon L, Maróti G, Nielsen L (2015). Rescheduling of railway rolling stock with dynamic passenger flows. Transportation Science, 49(2): 165–184

Li B, Yao E, Yamamoto T, Huan N, Liu S (2020a). Passenger travel behavior analysis under unplanned metro service disruption: Using stated preference data in Guangzhou, China. Journal of Transportation Engineering, Part A: Systems, 146(2): 04019069

Li B, Yao E, Yamamoto T, Tang Y, Liu S (2020b). Exploring behavioral heterogeneities of metro passenger’s travel plan choice under unplanned service disruption with uncertainty. Transportation Research Part A: Policy and Practice, 141: 294–306

Li Z, Yin J, Chai S, Tang T, Yang L (2023). Optimization of system resilience in urban rail systems: Train rescheduling considering congestions of stations. Computers & Industrial Engineering, 185: 109657

Liang J, Wu J, Qu Y, Yin H, Qu X, Gao Z (2019). Robust bus bridging service design under rail transit system disruptions. Transportation Research Part E: Logistics and Transportation Review, 132: 97–116

Liu K, Zhu J, Wang M (2021a). An event-based probabilistic model of disruption risk to urban metro networks. Transportation Research Part A: Policy and Practice, 147: 93–105

Liu T, Ma Z, Koutsopoulos H N (2021b). Unplanned disruption analysis in urban railway systems using smart card data. Urban Rail Transit, 7(3): 177–190

Louwerse I, Huisman D (2014). Adjusting a railway timetable in case of partial or complete blockades. European Journal of Operational Research, 235(3): 583–593

Luo C, Xu L (2021). Railway disruption management: Designing bus bridging services under uncertainty. Computers & Operations Research, 131: 105284

Moccia L, Giallombardo G, Laporte G (2017). Models for technology choice in a transit corridor with elastic demand. Transportation Research Part B: Methodological, 104: 733–756

Monsuur F, Enoch M, Quddus M, Meek S (2021). Modelling the impact of rail delays on passenger satisfaction. Transportation Research Part A: Policy and Practice, 152: 19–35

Niu H, Zhou X (2013). Optimizing urban rail timetable under time-dependent demand and oversaturated conditions. Transportation Research Part C: Emerging Technologies, 36: 212–230

Pender B M, Currie G, Delbosc A R, Shiwakoti N (2012). Planning for the unplanned: An international review of current approaches to service disruption management of railways. In: Australasian Transport Research Forum. Perth, 1–17

Pender B, Currie G, Delbosc A, Shiwakoti N (2014). Improving bus bridging responses via satellite bus reserve locations. Journal of Transport Geography, 34: 202–210

Pender B, Currie G, Shiwakoti N, Delbosc A (2015). Economic viability of bus bridging reserves for fast response to unplanned passenger rail disruption. Transportation Research Record: Journal of the Transportation Research Board, 2537(1): 13–22

Pnevmatikou A M, Karlaftis M G, Kepaptsoglou K (2015). Metro service disruptions: How do people choose to travel? Transportation, 42(6): 933–949

Sun H, Wu J, Wu L, Yan X, Gao Z (2016). Estimating the influence of common disruptions on urban rail transit networks. Transportation Research Part A: Policy and Practice, 94: 62–75

Tan Z, Xu M, Meng Q, Li Z C (2020). Evacuating metro passengers via the urban bus system under uncertain disruption recovery time and heterogeneous risk-taking behaviour. Transportation Research Part C: Emerging Technologies, 119: 102761

Tang J, Xu L, Luo C, Ng T S A (2021). Multi-disruption resilience assessment of rail transit systems with optimized commuter flows. Reliability Engineering & System Safety, 214: 107715

Tessitore M L, Samà M, D’Ariano A, Hélouet L, Pacciarelli D (2022). A simulation-optimization framework for traffic disturbance recovery in metro systems. Transportation Research Part C: Emerging Technologies, 136: 103525

van der Hurk E, Koutsopoulos H N, Wilson N, Kroon L G, Maróti G (2016). Shuttle planning for link closures in urban public transport networks. Transportation Science, 50(3): 947–965

van der Hurk E, Kroon L, Maróti G (2018). Passenger advice and rolling stock rescheduling under uncertainty for disruption management. Transportation Science, 52(6): 1391–1411

Veelenturf L P, Kroon L G, Maróti G (2017). Passenger oriented railway disruption management by adapting timetables and rolling stock schedules. Transportation Research Part C: Emerging Technologies, 80: 133–147

Wang J, Yuan Z, Cao Z, Lu Z (2021a). Optimal bus bridging schedule with transfer passenger demand during disruptions of urban rail transit. Journal of Transportation Engineering, Part A: Systems, 147(10): 04021071

Wang J, Yuan Z, Yin Y (2019). Optimization of bus bridging service under unexpected metro disruptions with dynamic passenger flows. Journal of Advanced Transportation, 6965728

Wang L, Jin J G, Sibul G, Wei Y (2023a). Designing metro network expansion: Deterministic and robust optimization models. Networks and Spatial Economics, 23(1): 317–347

Wang X, Jin J G, Sun L (2022). Real-time dispatching of operating buses during unplanned disruptions to urban rail transit system. Transportation Research Part C: Emerging Technologies, 139: 103696

Wang Y, D'Ariano A, Yin J, Meng L, Tang T, Ning B (2018). Passenger demand oriented train scheduling and rolling stock circulation planning for an urban rail transit line. Transportation Research Part B: Methodological, 118: 193–227

Wang Y, Guo J, Currie G, Ceder A, Dong W, Pender B (2014). Bus bridging disruption in rail services with frustrated and impatient passengers. IEEE Transactions on Intelligent Transportation Systems, 15(5): 2014–2023

Wang Y, Yan X, Zhou Y, Zhang W (2016). A feeder-bus dispatch planning model for emergency evacuation in urban rail transit corridors. PLoS One, 11(9): e0161644

Wang Y, Zhao K, D'Ariano A, Niu R, Li S, Luan X (2021b). Real-time integrated train rescheduling and rolling stock circulation planning for a metro line under disruptions. Transportation Research Part B: Methodological, 152: 87–117

Wang Y, Zhou Y, Yang H, Yan X (2023b). Integrated optimization of bus bridging service design and passenger assignment in response to urban rail transit disruptions. Transportation Research Part C: Emerging Technologies, 150: 104098

Xu L, Ng T S, Costa A (2021a). Optimizing disruption tolerance for rail transit networks under uncertainty. Transportation Science, 55(5): 1206–1225

Xu X, Chen A, Jansuwan S, Yang C, Ryu S (2018). Transportation network redundancy: Complementary measures and computational methods. Transportation Research Part B: Methodological, 114: 68–85

Xu X, Chen A, Xu G, Yang C, Lam W H K (2021b). Enhancing network resilience by adding redundancy to road networks. Transportation Research Part E: Logistics and Transportation Review, 154: 102448

Xu X, Li K, Yang L (2016). Rescheduling subway trains by a discrete event model considering service balance performance. Applied Mathematical Modelling, 40(2): 1446–1466

Xu Z, Chopra S S (2022). Network-based assessment of metro infrastructure with a spatial–temporal resilience cycle framework. Reliability Engineering & System Safety, 223: 108434

Yang J, Jin J G, Wu J, Jiang X (2017). Optimizing passenger flow control and bus-bridging service for commuting metro lines. Computer-Aided Civil and Infrastructure Engineering, 32(6): 458–473

Yang Z, Chen X (2019). Compensation decisions on disruption recovery service in urban rail transit. Promet, 31(4): 367–375

Yin H, Wu J, Sun H, Qu Y, Yang X, Wang B (2018). Optimal bus-bridging service under a metro station disruption. Journal of Advanced Transportation, 2758652

Yuan J, Gao Y, Li S, Liu P, Yang L (2022a). Integrated optimization of train timetable, rolling stock assignment and short-turning strategy for a metro line. European Journal of Operational Research, 301(3): 855–874

Yuan J, Jones D, Nicholson G (2022b). Flexible real-time railway crew rescheduling using Depth-first search. Journal of Rail Transport Planning & Management, 24: 100353

Zhan S, Wong S C, Shang P, Peng Q, Xie J, Lo S M (2021). Integrated railway timetable rescheduling and dynamic passenger routing during a complete blockage. Transportation Research Part B: Methodological, 143: 86–123

Zhang N, Graham D J, Hörcher D, Bansal P (2021a). A causal inference approach to measure the vulnerability of urban metro systems. Transportation, 48(6): 3269–3300

Zhang S, Lo H K (2018). Metro disruption management: Optimal initiation time of substitute bus services under uncertain system recovery time. Transportation Research Part C: Emerging Technologies, 97: 409–427

Zhang S, Lo H K (2020). Metro disruption management: Contracting substitute bus service under uncertain system recovery time. Transportation Research Part C: Emerging Technologies, 110: 98–122

Zhang S, Lo H K, Ng K F, Chen G (2021b). Metro system disruption management and substitute bus service: A systematic review and future directions. Transport Reviews, 41(2): 230–251

Zheng S, Liu Y, Lin Y, Wang Q, Yang H, Chen B (2022). Bridging strategy for the disruption of metro considering the reliability of transportation system: Metro and conventional bus network. Reliability Engineering & System Safety, 225: 108585

Zhou H, Qi J, Yang L, Shi J, Mo P (2022). Joint optimization of train scheduling and rolling stock circulation planning with passenger flow control on tidal overcrowded metro lines. Transportation Research Part C: Emerging Technologies, 140: 103708

Zhu J, Xu X, Wang Z (2023). Economic evaluation of redundancy design for transportation networks under disruptions: Framework and case study. Transport Policy, 142: 70–83

Zhu Y, Goverde R M P (2019). Railway timetable rescheduling with flexible stopping and flexible short-turning during disruptions. Transportation Research Part B: Methodological, 123: 149–181

Zhu Y, Goverde R M P (2020). Integrated timetable rescheduling and passenger reassignment during railway disruptions. Transportation Research Part B: Methodological, 140: 282–314

Zhu Y, Goverde R M P (2021). Dynamic railway timetable rescheduling for multiple connected disruptions. Transportation Research Part C: Emerging Technologies, 125: 103080