

Resilience concepts in integrated urban transport: a comprehensive review on multi-mode framework

Integrated
urban
transport

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Abstract

Purpose – Resilience concepts in integrated urban transport refer to the performance of dealing with external shock and the ability to continue to provide transportation services of all modes. A robust transportation resilience is a goal in pursuing transportation sustainability. Under this specified context, while before the perturbations, robustness refers to the degree of the system's capability of functioning according to its design specifications on integrated modes and routes, redundancy is the degree of duplication of traffic routes and alternative modes to maintain persistency of service in case of perturbations. While after the perturbations, resourcefulness refers to the capacity to identify operational problems in the system, prioritize interventions and mobilize necessary material/ human resources to recover all the routes and modes, rapidity is the speed of complete recovery of all modes and traffic routes in the urban area. These “4R” are the most critical components of urban integrated resilience.

Design/methodology/approach – The trends of transportation resilience's connotation, metrics and strategies are summarized from the literature. A framework is introduced on both qualitative characteristics and quantitative metrics of transportation resilience. Using both model-based and mode-free methodologies that measure resilience in attributes, topology and system performance provides a benchmark for evaluating the mechanism of resilience changes during the perturbation. Correspondingly, different pre-perturbation and post-perturbation strategies for enhancing resilience under multi-mode scenarios are reviewed and summarized.

Findings – Cyber-physic transportation system (CPS) is a more targeted solution to resilience issues in transportation. A well-designed CPS can be applied to improve transport resilience facing different perturbations. The CPS ensures the independence and integrity of every child element within each functional zone while reacting rapidly.

Originality/value – This paper provides a more comprehensive understanding of transportation resilience in terms of integrated urban transport. The fundamental characteristics and strategies for resilience are summarized and elaborated. As little research has shed light on the resilience concepts in integrated urban transport, the findings from this paper point out the development trend of a resilient transportation system for digital and data-driven management.

Keywords Cyber-physical system, Enhancing strategies, Integrated urban transport, Transportation resilience

Paper type Literature review

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1. Introduction

The word “resilience” originates from the Latin word “resiliere” which means “bounce-back” or “flexibility.” [Holling \(1973\)](#) first conceptualized “resilience” in the context of ecological systems and classified the distinction between resilience and stability. The concept of resilience has been introduced to different disciplines, including economics ([Rose and Liao, 2005](#)), social science ([Barnett, 2007](#)), system science and engineering ([E. Hollnagel et al., 2006](#)). The concept of resilience has been introduced and expanded in the transportation discipline, especially in recent years. Thus, there are no universal definitions for transportation resilience. While addressing the detailed resilience concept in transportation, there are two mainstream ways of defining transportation resilience ([Perrings, 1998](#)). One focused the disruption that could be absorbed before the transportation system is degraded to a worse state. According to [Holling \(1973\)](#), this way is not determined whether the system itself is near an equilibrium state or not. The other evaluated the ability to maintain regular operation after a disruption, which is usually described as the decrease in system performance ([Chopra et al., 2016](#); [Murray-Tuite, 2006a, 2006b](#); [Ta, Goodchild et al., 2009](#)). Hence, transportation resilience could be described covered both pre-disaster impact absorption and post-disaster. The definition of resilience corresponds to the swift recover ability as “the ability of transportation system to respond to, absorb the incoming perturbations to maintain its basic functions, and recover the service level at an appropriate cost” ([Wan et al., 2018](#)).

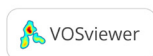
Perturbation influences transportation resilience by influencing its performance metrics such as robustness, flexibility and reliability. Perturbations could be either routine systematic fluctuation or rare catastrophic events. Those challenge the ability of disturbance resistance and performance recovery inevitably. For the rare and immense natural disasters like tornados or earthquakes, the transportation system would inevitably deviate away from the equilibrium states so far. The performance of the system to reduce efficiently both the magnitude and duration of deviation from designed performance levels is the most significant connotation of resilience ([Chopra et al., 2016](#)). However, in response to the everyday small-scale perturbations, a well-organized transportation system that bears the initial shock and maintains its overall function could make a real difference.

With the development of modern society and technology, transportation systems grow more complex, unpredictable and independent. Thus, the vulnerability of the system rises and unexpected perturbations such as extreme weather, congestions, accidents and infrastructure failures are more easy to penetrate and affect its functionality. Therefore, its resilience concept has developed more precise implications, varying from various levels involved by the urban multi-mode transportation system. On the design level, it implies that the entire system has been designed with several specific features to deal with unexpected circumstances. On passengers’ level, transportation resilience implies the capability to continue their traveling and remain productive even if suffering from traffic breakdown, congestion, infrastructure failure or other incidents. On the network level, it implies that the transportation network is accessible and available so that traffic can proceed under the effects of accidents, emergencies, seasonal construction projects or special events. On the mode level, it implies that various public and private modes could keep functioning smoothly in the same roadway, but every mode has independence itself. On the futurity level, it implies that a thorough system is ready to transform and upgrade for the possible usage and new pattern. It also has the potential to accommodate the incoming trends.

No matter on whichever level, transportation resilience would be the most significant concern to individuals and communities. It has a great significance for us to research the blueprint to enhance resilience, as it is critical to the sustainability development of

The general outline of this paper is listed in [Figure 2](#). In Section 2, a literature review is conducted on the distinctive characteristics of multi-mode transportation resilience, followed by qualitative and quantitative categorization and interpretation. In Section 3, the quantitative metrics and assessment methodology are conducted on the operational mechanism of the resilience under different modes. In Section 4, the strategies related to the cyber-physical transportation system in improving transportation resilience are classified and researched in various mode scenarios. Section 5 discusses the potential future trends and research directions in the last section.

The characteristic of transportation resilience proposes an intuitionistic representation of its definition and should be simplified, well-investigated and measurable. Bruneau *et al.* (2003) first presented a resilience framework, indicating that resilience could be characterized by four typical characteristics of resilient systems, which covered both phases in defining transportation resilience. This “4R” characteristic framework named by Tierney and Bruneau (2007) for transportation resilience contains four core properties: robustness, redundancy to describe the ability to maintain functionality at the disruption phase, resourcefulness and rapidity to describe the speed of recovery at the recovery phase.



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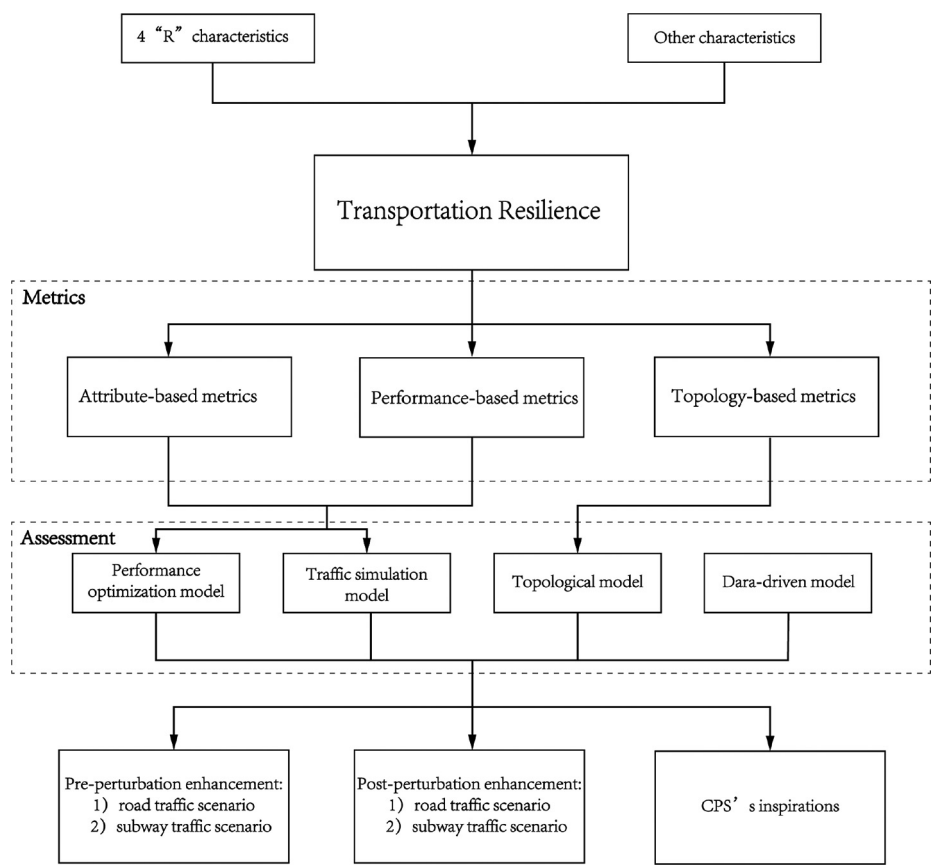


Figure 2.
Research framework

Robustness represents the ability to respond to or withstand various disruptive events without significant network or infrastructure functional degradation. Specifically, the concept of robustness embodies the critical nodes in the transportation network (e.g. network connectivity) and demand or capacity level in the realistic operation (e.g. route capacity and travel time). Redundancy means the duplication of critical functions of the system applying back-up functional modules (Leobons *et al.*, 2019). For instance, more alternative routes between origin-destination pairs (ODs) in transportation network and more transportation modes indicate a higher redundancy level of the system. Resourcefulness represents the availability of materials, supplies and crews in transportation system to restore its original functionality. The availability of resourcefulness also represents the enrichment of assets (e.g. people and materials) in the system and the power to spare those assets to the appropriate places in the proper timing, while rapidity, which is a very straightforward characteristic, evaluates the transportation system's speed to restore functionality. More rapidity indicates the system has a more vital ability to retrieve its normal service level in a timelier manner.

Also, Bruneau *et al.* (2003) introduced the resilience triangle to elaborate further their framework in Figure 3: the idea of the resilience triangle indicates that the perturbation

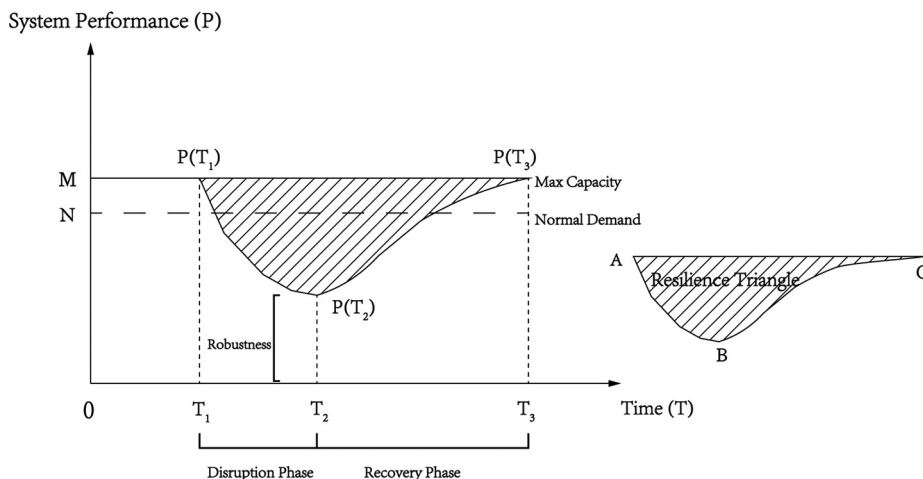


Figure 3.
Resilience triangle
diagram by the
concept of Bruneau
et al. (2003)

causes the sudden decrease of system performance at the time point T_1 ; then, the system performance gradually increases from the minimum performance level at the time point T_2 , where time interval $[T_1, T_2]$ corresponds to robustness and redundancy; finally, the system retrieves at a time point T_3 , where time interval $[T_1, T_2]$ corresponds to resourcefulness and rapidity. The resilience triangle focuses on its three edges: the first edge represents the time to reach the worst state, the second means the recovery time of functionality and the third edge indicates the recovery speed to normal condition (rapidity).

In addition to the classical “4R” characteristic framework, the subsequent scholars and researchers continue to add new connotation to the framework. At the disruption phase from the disaster begins to it ends, Berle *et al.* (2011) introduced preparedness as to “prepare certain measures before perturbation happens.” It is subdivided as emergency preparedness and response preparedness; it improves transportation resilience by lessening potential negative impacts of certain types of perturbation (Jin, Tang, Sun, and Lee, 2014). Also, Asbjørnslett and Rausand (1999) introduced vulnerability as “the susceptibility to damage or perturbation, especially those that are enormously destructive.” It is also regarded as the property of a transportation system that may weaken or constrain its ability to endure, handle and survive threats and disruptive events that originate both within and outside the system boundaries (Blockley *et al.*, 2012). Bhamra *et al.* (2011) proposed adaptability (or adaptive capacity) to reflect the system’s flexibility to respond to new pressures. Its essences lie in response to changes in different magnitudes, reflecting the dynamic and complex nature of transportation systems’ operational mechanisms (Dalziel and McManus, 2004; Fiksel, 2003). Similarly, flexibility is the capacity to respond and adjust to any changes during the perturbation. According to Berle *et al.* (2013), flexibility is also referred to as a transportation system to reconfigure resources and cope with uncertainties. Thus, the connotation of flexibility contrasts with that of robustness because flexibility emphasizes the aspect of withstanding or sustaining any changes by perturbation instead of the aspect of adapting to them (Cox *et al.*, 2011; Goetz and Szyliowicz, 1997).

Besides, at the recovery phase from the disaster ends to system recovery ends, Baroud *et al.* (2014a, 2014b) emphasized the idea of recoverability, which is discussed in many studies. Like rapidity, it refers to the ability to recover an acceptable proportion of functionality from the existing perturbation at the minimum cost. Furthermore, they define

“survivability” as the ability to withstand sudden perturbations persistently until meeting the original demand (Baroud *et al.*, 2014a, 2014b). Related to the vulnerability concept, survivability techniques have been considered as an access to dealing with the vulnerability issues of a transportation network (Faturechi and Miller-Hooks, 2014). Barker *et al.* (2013) referred to reliability as another characteristic to the probability that a system or specific network remains operative given the occurrence of a perturbation. It can be converted to either a pre- or post-perturbation metric for measuring resilience performance (Faturechi and Miller-Hooks, 2014).

3. Assessment of urban transportation resilience

There are two main steps in the process of measuring transportation resilience. The first introduces metrics for measurement, and the second calculates the metric with various evaluation approaches. Therefore, we will review the metrics and measurement approaches in this section.

3.1 Metrics of transportation resilience

The quantification resilience has been challenging since Murray-Tuite (2006a, 2006b) suggested some qualitative dimensions or characteristics are difficult to quantify; thus, no widely accepted quantification of them is available for the transportation system. Therefore, choosing appropriate resilience metrics is the most critical step before measuring transportation resilience. The spectrum of suitable qualitative characteristics can be expanded to use investigated or easily accessible metrics used for these components, such as vulnerability and reliability (Faturechi and Miller-Hooks, 2015, Gu *et al.*, 2020; Ahmed *et al.*, 2019).

Leonbons *et al.* (2019) interpreted the selection processes of the resilience metrics of transportation systems from one or both of the following two perspectives: the ability to maintain functionality under disruptions and the time and resources required to restore performance level after perturbations. Zhou *et al.* (2019) summarized various quantitative metrics research and concluded that those metrics could be roughly divided into three different categories with different levels of complexity, representativeness, effectiveness and depth: attribute-, performance- and topology-based metrics of transportation resilience.

3.1.1 Attribute-based metrics. As mentioned in Section 2, the classical framework to describe transportation resilience consists of four attributes: robustness, redundancy, resourcefulness and rapidity. In addition to that, much research extends the framework with other attributes. Attribute-based metrics directly quantify some attributes on the performance only at special periods.

In the pre-perturbation (disruption) phase, Hua and Ong (2017) used total unaffected passenger flow to describe the extent of robustness. Beiler *et al.* (2013) calculated redundancy as the alternative routes between critical ODs and mentioned a travel time index as “travel time in peak hours under normal conditions,” while Soltani-Sobh *et al.* (2016) proposed the operational cost and expected failure cost as indicators to distinguish the influence caused by a specific perturbation. Besides, Yoo and Yeo (2016) introduced adaptive capacity metrics by calculating the number or area in which adjacent nodes can replace an attacked node. Murray-Tuite (2006a, 2006b) quantified adaptability by the atypical uses of the transportation system, safety by the number of traffic incidents and mobility by the networkwide efficiency.

In the post-perturbation (recovery) phase, the resilience triangle in Figure 1 indicates T_3-T_2 as the restoration time, $P(T_1)$ as the maximum performance, $P(T_2)$ as the robustness of the system and $[P(T_3) - P(T_2)]/(T_3-T_2)$ as the rapidity of recovery, which are the outcome of

robustness, redundancy and resourcefulness (Tierney and Bruneau, 2007). Wang *et al.* (2015) represented rapidity as the speed of the system returning to the normal state and recovery as the time required to alleviate the systematic disarray. Furthermore, D'Lima and Medda (2015) emphasized recoverability on the cost and speed of returning to a new equilibrium.

3.1.2 Performance-based resilience metrics. Unlike attribute-based metrics, performance-based metrics aim to assess the performance of the transportation system during the whole affected period. Zhou *et al.* (2019) identified and sort out three of the most widely used performance-based metrics in previous literature. The first one is the time-based degradation of system performance proposed by Twumasi-Boakye and Sobanjo (2018). The second is the time-dependent ratio of recovery on quantifying performance loss by Liao *et al.* (2018). The third is the expected fraction of demand satisfied in post-perturbation phase using the recovery costs algorithm introduced by Chen and Miller-Hooks (2012).

The resilience index is first defined by Reed *et al.* (2009) equation (1), and it is based on the concept of the resilience triangle. According to Figure 1, where $R(T)$ is the resilience index at time point T , T_1 is the time point when the perturbation begins. Similarly, as displayed in equation (2), $Q(T)$ is the performance percentage of the specified transportation system, t is the timestamp when perturbation first occurs and $t + \alpha$ is the timestamp when the system's performance completely recovers. Their theory described resilience by the metric of performance loss from the full system performance during the whole disruptive event. It is not surprising that the value of $Q(T)$ is equal to the area of the resilience triangle in Figure 1.

$$R(T) = \frac{\int_{T_1}^T P(T) dT}{T - T_1} \quad R(T) = \frac{\int_{T_1}^T P(T) dT}{T - T_1} \quad (1)$$

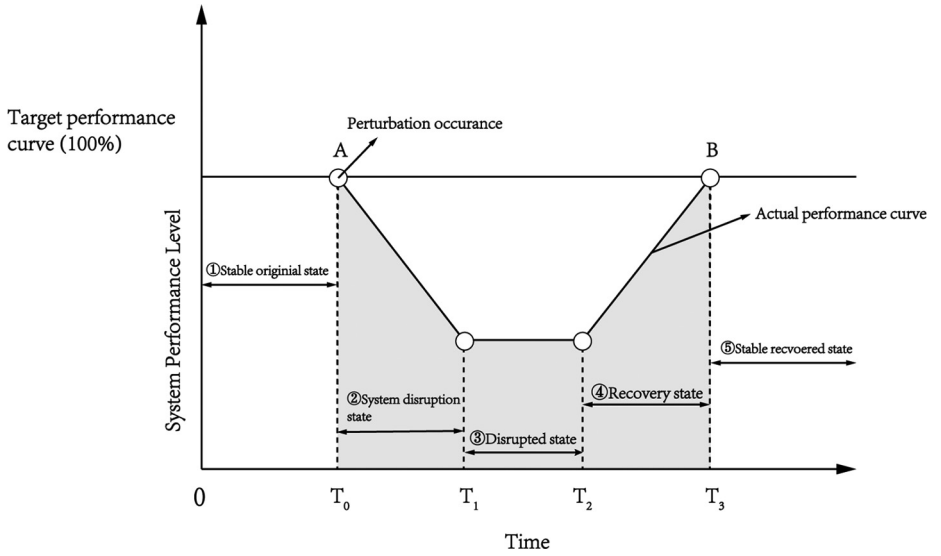
$$R = \int_t^{t+\alpha} [100 - Q(t)] dt \quad (2)$$

Then this algorithm of system performance was modified and improved by Bocchini and Frangopol (2012) and Adjetey-Bahun *et al.* (2016). As shown in equation (3), the metric of performance loss in equation (1) is divided by the time interval α between perturbation first occurs and system's performance completely recovers. In the modified algorithm, resilience is measured by the metric of average performance loss over the specified time interval α .

$$R = \int_t^{t+\alpha} \frac{[100 - Q(t)] dt}{\alpha} \quad (3)$$

Liao *et al.* (2018) introduced five system states in the whole perturbative event in Figure 4: original stable state, system disruption state, disrupted state, recovery state and stable recovered state. The five states are the important watershed for the time-dependent metric of transportation resilience. The metric is the ratio of recovery at the time t_i to function loss at other specified time points. As shown in equation (4), $R_F(t_i | p_j)$ is the resilience metric at the time t_i under the resilience perturbation p_j , while $F(t_i | p_j)$ is the function of system performance at the time point t_i with the perturbation p_j . t_o is the function of the system at original stable state. $F(t_m | p_j)$ is the minimum function. In this algorithm, transportation resilience is treated as a more dynamic concept and is more consistent with the ability to bounce back.

Figure 4.
A typical system
performance
response curve



$$R_F(t_i|p_j) = \frac{F(t_i|p_j) - F(t_m|p_j)}{F(t_0) - F(t_m|p_j)} \quad (4)$$

Chen and Miller-Hooks (2012) proposed another widely used metric which is usually used in the resilience in road and metro networks. The expected fraction of demand satisfied in the post-perturbation phase using the recovery costs is calculated in equation (5), where d_w is the maximum demand satisfied with the OD pair w at the post-perturbation phase and D_w is the demand satisfied with the same OD pair at the pre-perturbation phase.

$$R = \frac{1}{\sum_{w \in W} D_w} * E \left(\sum_{w \in W} d_w \right) \quad (5)$$

Furthermore, Omer *et al.* (2012) used the travel time as a critical metric for transportation system performance. Similar to Twumasi-Boakye's algorithm, the dynamic trends of resilience over time are represented in equation (6), where $t_{ij}^{(pre-perturbation)}$ represents the travel time during the pre-perturbation phase between node i and j , while $t_{ij}^{(post-perturbation)}$ indicates the travel time during the pre-perturbation phase between node i and j . Also, in the rail transit system, days of lost service (LSDs) are used to measure its resilience (Chan and Schofer, 2016). LSD can be generalized to study the resilience of public transportation systems facing severe perturbations such as extreme weather events (Zhou *et al.*, 2019). Equation (7) shows how LSD is calculated, where RVM_P represents revenue vehicle miles per day at disrupted state, RVM_o is that at the original stable state, t_0 is the time point when perturbation first occurs and t is the time when the system retrieves its normal service level.

$$R = \frac{\int_0^t \frac{t_{ij}^{(pre-perturbation)}}{t_{ij}^{(post-perturbation)}} dt}{t} \quad (6)$$

$$LSD = \sum_{t_0}^t \frac{RVM_o - RVM_D}{RVM_O} \quad (7)$$

In addition to the metrics that measure time costs above, [Vugrin et al. \(2014\)](#) tried to specify the amount of resource expenditures required for recovery using two metrics. In [equation \(8\)](#), the recovery effort in total (E) is calculated as the sum of resource expenditures on recovery task j on the route i in mode k at the time point t . b_{ijkt} is a binary variable judging if this certain recovery task is successfully completed. Then, the impact of perturbation on system performance (SI) is represented by the total cost because of insufficient flow capacity in [equation \(9\)](#), where C_i is the cost on route i and C_{i_0} is the cost at the pre-perturbation phase. α_{OD} is a coefficient of extra penalty costs; D_{OD} is the portion of travel demand exceeding current capacity at the OD pair l - m . Finally, the resilience could be represented as the sum of E and SI in [equation \(10\)](#), where β is a weighting coefficient.

$$E = \sum_i \sum_j \sum_k \sum_t RE_{ijk} * b_{ijkt} \quad (8)$$

$$SI = \sum_{t_0}^t \left[\sum_i (C_i - C_{i_0}) - \sum_{lm} \alpha_{lm} D_{lm} \right] \quad (9)$$

$$R = E + \beta * SI \quad (10)$$

Compared to the attributed-based metrics, performance-based metrics are more reasonable for describing the transportation resilience because they have fully covered the performance of the transportation system since the perturbation first occurred. Some of the metrics also cover time cost and resource expenditure and the ability to sustain during the disruptive event, which all make them more robust and comprehensive.

3.1.3 Topology-based metrics. Topology-based metrics focus more on the transportation network structure than its internal dynamic nature. They are built up with the basic graph-based properties such as nodes and traffic flow links of the transportation network. Thus, they are also called “centrality metrics.” [Schintler et al. \(2007\)](#) and [Berge et al. \(2009\)](#) proposed two widely used topology-based network parameters: average shortest paths and size of giant components. Both reflect the capacity that the transportation network keeps connected during the perturbation. According to [Schintler et al. \(2007\)](#), average shortest paths assess the strength of transportation network connection. The size of giant components reflects the percentage of links and nodes that remain functional during the perturbation. Besides, [Aydin et al. \(2018\)](#) introduced the concept of network betweenness centrality and efficiency. Osei-Asamoah and Lownes proposed network efficiency further as a metric in [equation \(11\)](#), where L_{ij} is the length of shortest path of node i – j .

$$E = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{L_{ij}} \quad (11)$$

In addition, [Ip and Wang \(2011\)](#) introduced a metric using the weighted number of reliable passageways to calculate the reliability of a certain node and the network resilience. In [equation \(12\)](#), ω_i and W_j are, respectively, the population weight and self-exhausted weight of the node i – j and $P_k(i, j)$ is calculated as the reliability of a passageway of the node i – j . [Hartmann \(2014\)](#) proposed the algorithm of network backup capacity (C_b) of node i – j in [equation \(13\)](#), where ΔB_{ij} is the increase of edge-betweenness after the removal of the edge of

with largest edge-betweenness. [Testa et al. \(2015\)](#) enriched the theory on betweenness centrality and further calculated network redundancy in [equation \(14\)](#), where NIP is the number of independent paths between node i to condition of the complete graph, $I(i, j)$ is the number of independent paths between node i - j and σ_i^2 is the neighborhood of the vertices in the neighborhood of i . In conclusion, these metrics are defined in different ways and forms, but their essence concentrates mostly on comparing the topological details of the transportation system with the corresponding complete graph.

$$R = \sum_{i=1}^n \omega_i \sum_{j=1, j \neq i}^n W_j \sum_{\forall k \text{ node}(i,j)} P_k(i, j) \quad (12)$$

$$C_b = \max_{ij} (\Delta B_{ij}) \quad (13)$$

$$Redundancy = \frac{1}{(|NIP| - 1)^2} \sum_{\forall j \in \sigma_i^2} I(i, j) \quad (14)$$

[Sun et al. \(2020\)](#) explored the cities' resilience in the global air transportation network to single airport perturbations. They used two types of passenger-focused topological metrics to quantify the impact on the resilience of cities' air transportation: The unaffected passengers and the reroutable passengers on aggregated (airport) links. A large fraction of unaffected passengers indicates that the airport perturbation has a small effect on the travelers, while a large fraction of reroutable passengers indicates that the airport disruption has a smaller effect on the travelers ([Sun et al., 2020](#)).

3.2 Methodology of assessment approaches

Though assessment methodologies may differ because of the available data, researchers' backgrounds and the level of network complexity they should address ([Serdar et al., 2022](#)), they gave an in-depth assessment of transportation resilience. The methodology could be summarized as follows.

3.2.1 Performance optimization model. The performance optimization model aims to promise the best results in the system's performance under multiple constraints. According to [Liao et al. \(2018\)](#), mathematical modeling and optimization methods in the performance optimization model are efficient and promising tools for measuring resilience. They could be either dynamic or static and can cover different modes. However, the suggested methods have limitations because the recovery measures' effectiveness is highly based on human judgment. The threats need to be identified using a yet-to-be-developed disaster database ([Liao et al., 2018](#)).

The dynamic traffic assignment (DTA) is a widespread and effective optimization model. [Sommer et al. \(2016\)](#) introduced only an optimization-based adaptive traffic signal system on vehicular modes. Its optimal objects are increasing the vehicular performance of the transportation system, controlling flow to provide a more stable traffic network and reducing congestions and vehicular stops. ([Sommer et al., 2016](#)). [Geroliminis and Sun \(2011\)](#) used a macroscopic fundamental diagram in the model to optimize the linking space-mean road traffic flow, density and speed existing in a large urban area. Their models both used the average vehicular flow on a network as a function of the number of vehicles with independent trip OD pairs and route choices inside a selected road system to evaluate its robustness and redundancy level.

For the multi-mode DTA, [Nogal et al. \(2016\)](#) introduced the dynamic system optimal equilibrium to a restricted DTA time-travel cost optimization model on all modes. An optimization model for multi-mode traffic is introduced by [Ye and Ukkusuri \(2015\)](#) for the recovery of the transportation system network calculating the most optimal sequence for recovery nodes, links and routes to optimize resilience in the maximum recovery rate and minimum recovery expenditures, while the effect of their model is highly depended on the post-perturbation resource priority management and systematic budget allocation. [Feixiong et al. \(2012\)](#) introduced the Supernetwork model to optimize travelers' choice of all modes. This model considers the real-world activity and trip chain and embedded travelers' preferences for transport modes and locations in the model. All the multi-mode models have their functions of interaction between modes to ensure optimization accuracy.

Though optimization models for multi-mode traffic are helpful in the recovery strategies at the post-perturbation phase, they also require a considerable number of computational resources, accurate mathematical formulation and strategic policy-supported goals to ensure their effectiveness ([Serdar et al., 2022](#)). The limitations of their model are the dependence on the network impedance value that is selected and quantified based on a series of questions in the user travel survey. This nature makes the model difficult to be extended to a large scale and significantly relies on the accuracy of the survey conducted ([Nogal et al., 2016](#)).

3.2.2 Traffic simulation model. The traffic simulation model examines the system's performance under both hypothetical and actual scenarios with precedent parameters. It is beneficial for detecting the critical functional components, systematic vulnerabilities and any other unexpected weak points. However, [Nkenyereye et al. \(2019\)](#) pointed out that its substantial processing capacity required the magnitude of what can be assessed, making the method difficult to scale up to the magnitude of urban transportation.

In most research, simulation is suitable for assessing unique characteristics of different modes of the transportation network. It is explicitly implemented to assess the performance metrics instead of tracking the changes of topological and other changes of the transportation network.

For road system simulation, [Murray-Tuite \(2006a, 2006b\)](#) the traffic assignment-simulation methodology DYNASMART-P generated system user equilibrium traffic assignments for a test network are sound to assess adaptability, mobility, safety and rapidity. [Duy et al. \(2019\)](#) combined the hydrological data with operational data of local road networks into the traffic simulation model to assess the resilience in a coastal city's transportation system under the impact of a flood disaster. [Ganin et al. \(2019\)](#) conducted a simulation model evaluating the selected intelligent traffic signals in the road system under cyber-attacks, and the resilience of the system under different scenarios is simulated. They formulated the data input such as transportation network density and average delay into the model of traffic signals effectiveness. The simulation result showed how much loss that the locking of signals could cause to the resilience than the normal infrastructure failure. ([Ganin et al., 2019](#)). The simulation outcome of this mode reflects the real process accurately, and the resilience change of the road system is examined under precedent metrics.

For railway system simulation, [Osei-Asamoah and Lownes \(2014\)](#) used a traffic simulation model to assess the resilience of railway transit in the urban transportation system by comparing the model outputs under normal situations and that with perturbations. The input performance metrics selected are travel time delay and ridership by hours (passengers entering each station in each hour). They assumed that these passengers were all to take the shortest way to the destination. The outcome of this mode is a little subjective based on its assumptions; the comparison between scenarios has a certain level of deviation.

The method is suitable for predicting future scenarios and detecting inconspicuous resilience problems. But its main limitation is resource-intensive and difficult to scale to accommodate urban or larger magnitude networks, while a more precise calibration transportation performance is also required.

3.2.3 Topological model. Corresponding to the topological metrics mentioned before, topological models focus on calculating the shortest paths and the size of giant components. Berche *et al.* (2009), Osei-Asamoah and Lownes (2014) and Ta *et al.* (2009) applied the topological model to calculate the shortest paths by the distribution of node degree. Dunn and Wilkinson (2016) and Yoo and Yeo (2016) calculated the size of giant components and network efficiency by detecting the proportion of nodes or links that is connected as a cluster under different perturbation scenarios. Unlike optimization models and simulation models, topological is simpler in form. It simplifies transportation systems into quantities of links (representing the direct routes between adjacent nodes) and nodes (representing intersections and OD points). It has wide applications in urban transportation, but it is best suited for water or air logistical transportation.

Calibrating the network's connectivity from nodes to links is the key for topological model to assess transportation resilience through topological metrics. For instance, Zhenwu *et al.* (2019) implemented the "percolation theory" to the network of Chinese cities through clusters of nodes to identify its vulnerable connections (Zhenwu *et al.*, 2019). Cerqueti, Ferraro and Iovanello (2019) used weighted links in the model to investigate the failure propagation (Cerqueti *et al.*, 2019). Testa *et al.* (2015) applied the connectivity to assess the resilience of a topological transportation network during the random disconnections of nodes and links. Then, an integrated program (SLOSH) was applied to detect the damaged links and nodes in the network and measure the resulting resilience under a storm surge (Testa *et al.*, 2015). Only when the connectivity calibrating is precise can the model be efficient in assessing the topological metrics of the network.

Though the topological model is relatively simple to develop and apply, it has certain limitations compared to optimization and simulation models. It cannot account for any accidents in the links, especially for accidents that could severely affect the network's capacity. It also ignores the different modes of traffic as well as their available alternatives in the nodes and links.

In addition, Zanin *et al.* (2018) urged that there are four major common pitfalls while applying the network theory to measure the topology of transportation systems. 1) The scale-freeness, which is the most important topological properties, requires both large enough networks and the application of suitable statistical tests to avoid obtaining biased results. 2) Beyond that, another pitfall that stems from topological metrics is highly associated with the number of nodes and links in the selected network. Thus, comparing different networks using same set of such metrics will lead to unreliable results. 3) Inappropriate choices of node sequence will result in unfounded conclusions comparing to the actual condition of real-world networks. Thus, there is a trade-off between the assessment of high-quality attack sequence and run time of the model, because the quality and run time both relate to the number of network nodes. The computation of variant betweenness needs to be appropriate in the large network. 4) Comparisons between random and targeted attacks have to be performed with care when specific metrics do not represent the node importance very well for the network (Zanin *et al.*, 2018).

3.2.4 Data-driven model. In recent years, because of data collection and storage development, data-driven methods have become a more efficient way to assess transportation resilience. Unlike the three mentioned methodologies, the data-driven method focuses on the direct data collected to calculate and assess the change of the system's

properties under different scenarios. However, it ignores the operation mechanism of the transportation system during the entire process. The essence of the data-driven model is choosing proper and representative data such as ridership, service frequency and vehicle miles traveled of different modes. Statistical methods are sometimes used to pre-process the data before being used as performance indicators (Zhou *et al.*, 2019).

One essential requirement for a data-driven model to assess transportation resilience is tracking the operational status and the performance of the system responding to perturbations. Donovan and Work (2017) built up their data-driven model to assess resilience by GPS data records from taxi sensors. The data they collected was travel distance and time of taxis. They used specific rules to remove some outliers and then normalized the trips by calculating the travel pace based on the travel distance and time changes throughout the week. Then the statistical Mahalanobis distance was applied to detect how the resilience is affected by special events (Donovan and Work, 2017). The tracking of system status is not only critical for assessing resilience but also one core requirement of cyber-physic transportation system (CPS).

Another critical requirement of the models to investigate the outcomes of perturbations is analyzing several types of data representing transportation systems. Diab and Shalaby (2019) applied the statistical analysis and filtering of metro line service records to assess resilience in terms of the “Lost Days of Service” because of the impact of perturbations (Diab and Shalaby, 2019). They collected time series data of metro series and retrieved data of metro networks and travelers’ behavior. Roy *et al.* (2019) used data from the social media platform in their data-driven model to assess how resilience was affected by earthquakes and storms. The diversity of data allows the model to comprehensively represent the system trends, where data from performance and topological aspects are helpful.

The efficiency and accuracy of the data-driven model depend on the data source availability, data filtering, data processing and data analytics. Any misrepresenting network properties, such as topography, capacity and actual physical damage, might lead to entirely opposite outcomes, misleading future performance predictions.

4. Strategies of enhancing resilience under various scenarios

Integrated urban transport perturbations vary in characteristics, impact scope, hazard degree, duration and randomness (Serdar *et al.*, 2022), as shown in Table 1. However, perturbations can be assigned to seven main categories: severe weather, natural disasters, terrorist attacks, transportation facilities collapse, traffic congestion, road construction and epidemic. Hence, the strategies for enhancing transportation resilience are reviewed based on different perturbations at different modes.

In addition to external perturbations, the current transportation system faces internal challenges in achieving resiliency. First, the primary structure of the transportation system is difficult to deconstruct, which indicates the sophisticated and coupling structures of the transportation system. Second, the real-time and historical traffic situation is difficult to deduce because of the uncertainties in perturbations. Third, the system controller is difficult to coordinate because there are few intra-system co-operational control methods to apply. Fourth, the resilient components of the transportation system are difficult to deploy because they are not applicable in various complex scenarios. Hence, the goal of these strategies below is to construct a new transportation system with an excellent ability on swiftly state perception, capacity expansion and network reconfiguration.

The requirement is summarized as four “could”: traffic status could be monitored, network operation could be highly controlled, reaction process could be tracked and the CPS

Table 1.
Summary of
transportation
system perturbations
and characteristics

Perturbation name	Characteristics	Impact scope	Hazard degree	Duration	Randomness
Severe weather Natural disasters	Abnormal shocks on the supply side	Small Large	Low medium High	Short Short medium	Predictable Random, sometimes predictable
	Abnormal shocks on the supply side				
Terrorist attacks Transportation facilities collapse	Abnormal shocks on the supply side	Medium-Large Small medium	High Vary	Short Short medium	Unpredictable Random, sometimes predictable
	Normal shocks on the demand side, including major events and holidays;				
	Normal shocks on the supply side, including bus delays and rail transit blocking				
Traffic congestion	Normal shocks on the supply side, including accidents	Small medium	Low medium	Short	Predictable
Road construction Epidemic	Normal shocks on the supply side	Small Medium large	Low Medium high	Short Medium long	Predictable Random, sometimes predictable
	Abnormal shocks on the supply side				

system could be implemented. Furthermore, it is also to set a new benchmark for the transportation planning, design, operation management, renewal and reconstruction of a new generation of transportation infrastructure which is dependable and robust under normal fluctuations and fast recovery under perturbations.

4.1 Pre-perturbation strategies of enhancing resilience

4.1.1 *The road traffic scenario.* According to the schematic of performance of a resilient system (Wan *et al.*, 2018), road system resistance to disturbance mainly goes through two stages: pre-perturbation and post-perturbation. In the pre-perturbation stage, the disturbance resistance strategies aim to maintain the system running in the original state and to keep the system capacity and demand unchanged according to the plan.

(1) Demand management

Macro demand management plays a vital role in improving the system's resilience in advance, and it is one of the most effective ways. Specific measures include releasing timely information (Brudny and Krawiec, 2013), encouraging the choice of different modes of transportation (Liu *et al.*, 2017) and increasing relevant incentive policies (Chen *et al.*, 2020). This strategy can effectively prevent the impact caused by transportation facilities collapse, traffic congestion and other disturbances.

Variable message sign (VMS) is a main platform to release guidance information. Yi *et al.* proposed a method for location optimization of urban VMS (Yi *et al.*, 2019). They also gave an evaluation model for existing VMS and the recommended frontal distance and the height of characters. Bus bridging or taxi bridging has been widely used to connect stations affected by disruptions which help passengers resume their journeys. A two-stage model was developed to optimize the bridging plan and its allocation to buses, with the goal of balancing operational priorities between minimizing bus bridging time and reducing passenger delays (Gu *et al.*, 2018). In addition, park and ride service is a part of comprehensive demand management. It has been proved that despite the complexity of finding parking spaces in the city center, park and ride services have made progress in alleviating traffic congestion (Memon *et al.*, 2014).

(2) Variable speed limits control

Variable speed limits (VSLs) have a positive impact on improving highway traffic safety and efficiency, especially for dealing with severe weather, traffic congestion and other disturbance types. VSL control adopts advanced traffic flow and traffic environment detection technology and automatically adjusts the current speed limit value based on the preset control strategy. It reflects the changing road traffic environment characteristics in real-time and releases the information to road users in real-time.

Based on the traffic flow theory, some scholars have studied the potential impact of VSLs on the traffic operation efficiency of the expressway, including using this technology to eliminate the shock wave (Popov *et al.*, 2008) in case of congestion in the bottleneck section, so as to maintain the traffic operation in the working area in a more uniform and stable state (Kwon *et al.*, 2007) and reduce the delay of isolated confluence area and confluence area (Carlson *et al.*, 2010).

The academic circles have not reached a unified understanding of the impact of VSL control on traffic capacity. The study of Dutch highway data showed that VSLs could not improve the capacity. In some recent studies, Karimi *et al.* (2004)

believed that the VSLs control is only to replace the part of the flow occupancy curve lower than the key occupancy rate with a straight line segment, and its slope represents the speed after the implementation of VSL. Its theory is that there is no improvement in traffic capacity. Papageorgiou (Carlson *et al.*, 2010) observed the traffic flow of a two-way six-lane road for 27 days, obtained the traffic flow characteristics under different speed limits and drew two conclusions: First, when the upstream occupancy rate of the mainline is lower than the key occupancy rate, the implementation of VSL control will reduce the average speed and increase the density, which can reduce the traffic flow to the bottleneck area, so as to delay or even eliminate the decline of traffic capacity in the downstream bottleneck area. Second, too low speed limit will reduce the capacity, and too high-speed limit will not affect the capacity.

(3) Infrastructure monitoring and maintenance

After long-term use, transportation infrastructure is constantly worn, resulting in deficient performance and diverse types of distress or damages (Hadjidemetriou *et al.*, 2020). Infrastructure maintenance management has become an effective means to alleviate transportation facilities collapse and other related disturbances. A World Bank study revealed that every 10% increase in road roughness led to a 5–20% reduction in road life (Janoff *et al.*, 1985; Smith *et al.*, 1997) and an additional 0.5–4.1% increase in fuel consumption (McLean and Foley, 1998). Therefore, early comprehensive performance inspection of road, bridges, culverts and tunnels together with the disposal of specific damages can bring sizable economic benefits as well as ensure facility operation quality and serviceability.

Maintenance units regularly patrol transportation infrastructure in jurisdictions to determine performance in time and consider disposal plans. However, on the one hand, traditional labor-based inspections are unsuitable for application in a wide range of transportation network considering their low efficiency and operational complexity. The timeliness of the inspection data is unable to meet the coverage rate. On the other hand, the increase in total facilities puts forward higher requirements for maintenance (Hormozabad *et al.*, 2021). It costs more efforts for the maintenance management department to effectively track and predict the decay trend of conditions. Although the compound growth rate of infrastructure maintenance investment has increased, it is difficult to ensure the rational distribution of huge maintenance funds.

4.1.2 The subway traffic scenario. As a large-volume transportation method in the city, subway traffic has high autonomy and operational complexity, which leads to its vulnerability (Bešinović, 2020). Under various emergencies such as natural disasters, equipment failures and man-made damages, it is prone to cascade failures and requires more time to recover. Therefore, the enhancing strategies of subway traffic resilience have been widely studied. Considering the resilience characteristics of subway traffic, strategies for pre-perturbation focuses on improving network vulnerability to unexpected changes. The overall resilience is improved by enhancing local resistance. Therefore, strategies for pre-perturbation can be categorized as influencing factor analysis, vulnerable elements identification and reinforcement and network structure optimization.

(1) Influencing factor analysis

Identifying the key influencing factors for subway traffic to resist perturbation is of great significance to ensure the normal operation of the subway and can help

managers to take corresponding protective measures. Previous studies have explored the influencing factors of resilience from the perspectives of comprehensive evaluation, scenario simulation analysis and control measures analysis.

Influencing factor analysis research are concerned with scenario specific. Researchers delved into weather-related disruptions and disasters in subway traffic, such as fire (Rie and Ryu, 2020; Giachetti *et al.*, 2017), earthquakes (Fan *et al.*, 2021), hurricanes (Zhu, Yuan, *et al.*, 2016; Zhu, Yuan, *et al.*, 2017) and weather conditions (Chan and Schofer, 2016; Diab and Shalaby, 2020; Wang *et al.*, 2020). Quan *et al.* (2011) used scenario simulation to focus on the impact of rainstorms with different return periods on the Shanghai Metro. Lyu (2018) conducted a flood risk assessment of Guangzhou's subway system, considering 12 factors such as rainfall, altitude, slope and subway line density. Aoki *et al.* (2016) analyzed the impact of different flood control equipment on the flood control capacity of subway stations. They concluded that the subway station entrance is the station most affected by heavy rain.

Usually, these studies estimated the frequency and duration of service interruptions. Moreover, the temporal and spatial distribution of disruptions and recovery processes under various perturbances are uncovered to provide planners with useful system design information. The influencing factor analysis strategy is based on historical data or simulation methods, which can accurately describe the resilience changes of system interruptions and provide a reference for future resilience regulation. However, there are problems of incomplete consideration factors and unrealistic model estimation. The reliability is supposed to be improved through more comprehensive data.

(2) Vulnerable elements identification and reinforcement

Vulnerable elements identification aims to find out the critical elements in the subway traffic system, which could lead to severe impacts when being failed. It usually requires evaluating the functional loss of the system based on assuming the failure of elements. The greater the loss, the higher the importance of the evaluated element. The corresponding reinforcement measures are applied to those vulnerable elements.

Vulnerable elements identification is conducted through topology analysis. Deng *et al.* (2015) proposed a new framework based on network theory and The Failure Mode, Effects and Criticality Analysis method to analyze network efficiency by network theory and risk matrix in The Failure Mode, Effects and Criticality Analysis method. King *et al.* (2020) used a combination of quantitative methods founded in Graph Theory to quantify the resilience of the transit network and identified the critical stations in Toronto's subway network. Jing *et al.* (2020) developed a new method to determine the critical stations in metro systems based on route redundancy. The results indicated that the critical stations are not necessarily transferred stations or large node degree stations. Regarding the vulnerability of network components, Bababeik *et al.* (2018) proposed a bi-objective location and allocation model for relief trains in the rail network, determining the optimal location and allocation of relief trains to enhance the resilience level of the rail network.

Vulnerability analysis strategies identify critical subway stations by modeling the service network. It could assist in a cost-effective resource allocation for strategically protecting the subway network and informed decision-making for

emergency evacuation planning. Note that because of the heterogeneity of the network and different importance evaluation criteria, analysis models should be robust against the failure and removal of randomly chosen network elements.

(3) Network structure optimization

Optimizing the topology of the subway traffic network is one of the effective ways to improve network resilience and mitigate network damage. Based on different perspectives, researchers evaluated the network structure from the aspects of network connectivity, service level, operational reliability and so on, which aimed to enhance the resilience through structure optimization.

Measure coefficients are taken as objective functions, and the construction cost is the constraint function to establish the network structure optimization model. When evaluating the reliability of network connectivity, most researchers choose the relative size of the largest connected subgraph (Wang, 2008), the connectivity probability of a node pair (Liu *et al.*, 2020) or the network efficiency (Zeng *et al.*, 2021) as the measurement parameters. The network service level can be measured by the increase rate of passenger travel cost (Hua and Ong, 2017) and network transmission capacity saturation (Liu *et al.*, 2020). Operational reliability usually refers to the reliability of network travel time, which can be measured by the average shortest travel time of the network and the rate of change of network nodes to the shortest travel time (Shi *et al.*, 2019).

Network topology optimization is to increase the number of backup nodes or lines to improve connectivity or increase the capacity of key nodes or lines to adapt to the distribution of passenger traffic. However, considering that the geographical location of subway network nodes often depends on passenger flow demand, this method's application is relatively limited.

4.2 Post-perturbation strategies of enhancing resilience

4.2.1 *The road traffic scenario.* In the post-perturbance, after system performance of road traffic declines, recovery strategies involve rebuilding system accessibility and restoring its functionality as quickly as possible.

(1) Variable lane management

Variable lane control has become an effective means to alleviate traffic congestion, road construction, epidemic and other disturbances in various countries. The variable lane control scheme is applied to tidal traffic flow on urban roads. In this scenario, the traffic flow in one direction is large or even congested. In contrast, the traffic flow in the other direction is small, resulting in idle road resources, waste of road resources and low traffic capacity. The network-based variable lane control method is analyzed theoretically in the existing research on variable lane (Pan *et al.*, 2022). By establishing a bilevel programming model (Meng and Khoo, 2008) based on the optimal system performance, the corresponding solution method is designed to calculate the attributes of variable lane control nodes (Wang *et al.*, 2013).

The main objects of variable lane management include road channelization, information control scheme and social vehicles. However, most of them only consider the variable lane control for a certain section to adjust the traffic flow of some tidal sections and do not improve the system capacity from the overall point of view. At the same time, this kind of technology is relatively slow to solve. For the variable lane adjustment under accident conditions, the focus is on the traffic evacuation speed after the accident, so the application scenarios are limited.

(2) Ramp control

From the perspective of system control, ramp control can be divided into three types: timing control, single point dynamic control and dynamic coordination control. They have a positive impact on dealing with severe weather, traffic congestion, epidemic and other disturbance types.

Timing control is the simplest ramp control method, which is a static control. The regulation rate of timed ramp control is one or more fixed values, which is determined based on analyzing the historical traffic information of the road section. Timed ramp control has the advantages of a simple algorithm, easy operation and convenient implementation, but it cannot correct the ramp regulation rate according to the real-time road traffic conditions.

To make up for the defects of the timing control algorithm, many scholars have studied single-point dynamic control. In this dynamic control, the detector should be used to detect the traffic information on the road in real-time, and on this basis, the adjustment rate of the matching road should be adjusted in real-time for dynamic control. Among them, ALINEA control is the most widely used method. This control method was proposed by Greek scholars (Frejo and De Schutter, 2019). In this method, a critical value of mainline occupancy is given in advance. If the detected occupancy is different from the given value in each detection cycle, then the original adjustment rate is adjusted.

Dynamic cooperative control is to regard several corresponding lanes on a fast road as a whole and determine the optimal regulation rate of each ramp through the road traffic information collected in real-time. The purpose of dynamic cooperative control is not to optimize the traffic operation of a ramp but to maximize the overall traffic benefit. Responding to traffic events or normal traffic phenomena can avoid or quickly eliminate frequent and occasional congestion. The main algorithms are ZONE (Geroliminis *et al.*, 2011), BOTTLENEC and HERO (Papamichail *et al.*, 2010).

Ramp control is equivalent to the regulator of traffic demand of expressway and ground roads, mainline and branch line of the expressway. It has a significant effect when the demand pressure is slight, but when the traffic pressure increases, this method will cause a vicious circle of queue extension. Therefore, a more global consideration method is needed for overall control.

4.2.2 The subway traffic scenario. The independence and openness of the subway traffic make it highly dependable in operation. At the same time, it is vulnerable to disturbance and damage from various emergencies such as natural disasters, equipment failures and artificial damages. Compared with other modes of transportation, the subway traffic takes longer to recover (Chen *et al.*, 2007). To prevent disturbances within the system from being further spread to road traffic, the immediate priority is passenger evacuation. While maintaining the service capacity of urban traffic leaves necessary space and time for the recovery of subway traffic. Given the above, strategies for post-perturbation can be bus-bridging and optimum recovery sequence decisions.

(1) Bus-bridging

Bus-bridging is an effective strategy in the contingency plan for subway emergencies and provides substantial support for passenger evacuation with its characteristics of rapidity, flexibility and accessibility. It can offer backup and continuation functions for the subway traffic during the reaction and recovery phase after an emergency.

The European Commission (2004) regarded the coordination of services, network layout and emergency support between rail transit and public transport as the technical basis for implementing combined public transport. In the research report of

TRB (2007), it was proposed that in the response and evacuation stages and the repair and service restoration stages after rail transit emergencies, the linkage support role of ground public transport should be imported to empower. Researchers studied the design of bus-bridging routes (Kuah and Perl, 1988; Martins and Pato, 1998; Deng *et al.*, 2018), the scheduling model (Kepaptsoglou and Karlaftis, 2009; Jin *et al.*, 2016; Itani and Shalaby, 2021), position of interchange stations (Tang *et al.*, 2021; Derrible and Kennedy, 2010a, 2010b), emergency bus capacity and site selection (Teng and Xu, 2010; Gu *et al.*, 2018) to introduce resilience enhancement in subway traffic.

Current studies emphasized the research on the emergency connection of public transport in the case of subway operation failure, and the optimization objectives and constraints considered are different. Most of them focused on the emergency rescue of trapped passengers after the subway traffic operation was interrupted. The collaboration of multi-mode transportation might be a future research hotspot.

(2) Optimum recovery sequence decisions

The damage of different components in the subway network has distinct effects on the network. Moreover, the recovery of damaged components often requires different amounts, types of recovery resources and costs a certain amount of repair time and economic costs. Therefore, when multiple components in the network are damaged, the repair sequence of different components plays a crucial role in improving network resilience.

Based on the optimal recovery objectives, the recovery sequence decision is to determine the optimal repair order of network failure units. Considering limited resources and costs, reasonable allocation and scheduling to optimize recovery resilience have received increasing concern. Zhang *et al.* (2018) determined the optimal recovery sequence and recovery time combined with the importance of nodes in the network. He also considered the performance cost after the subway interruption, including the loss of operating income and maintenance measures. Lu (2018) quantified the varying resilience of rail networks with time under different incidents, and the results showed that critical stations were identified differently depending on the duration time of different incidents and the characteristics of the failed stations. Jie-fei *et al.* (2020) and Qingchang *et al.* (2021) proposed resilience indexes to evaluate the performance of subway network resilience under different restoration schemes and recommend the scheme with the largest resilience index as the optimal scheme.

Most studies usually build models based on the simplification of subway traffic networks and determine the optimal recovery sequence with the goal of minimum performance loss, shortest repair time and minimum recovery cost. But some practical factors, such as the physical length of tunnels between stations, the time and route of changing subway lines and subway lines with different volumes, are not included in the model.

(3) Network self-organization adjustment

The subway network consists of a large number of interacting nodes and links. Any adverse event that disrupts network component interactions and connectivity can significantly impact safety and efficiency. Therefore, it is important to maintain the connectivity of the line after the perturbation and reduce the impact of interruption caused by the interference without significantly reducing the network service capacity.

Network self-organization is an effective method to increase regional resilience. For vulnerable nodes like transfer stations, adding an interloop could create redundancy to these vulnerable segments and improve network resilience by increasing network efficiency. Saadat *et al.* (2020) examined three alternatives to implanting loops in a

network, each inserted based on subjective considerations such as location criticality, passenger flow and location connectivity. The results showed that network vulnerabilities can be significantly reduced by adding loops. Inserting a loop can reduce vulnerability by 24.6% on certain road segments. [Derrible and Kennedy's\(2010a, 2010b\)](#) research showed that the number of looping paths available in a network significantly affected network resilience, which represented whether alternative routes could be used in an outage.

As a post-perturbation recovery strategy, network self-organization adjustment can restore connectedness and reduce the total cost associated with a disruptive event. It would play a better control effect by combining bus-bridging and multi-mode transportation strategies.

4.3 Inspirations of possible cyber-physic transportation system applications on future resilience enhancement

Performance improvement strategies in the post-perturbance stage are active prevention and control technology, which is a series of behaviors, to realize active prevention, early warning, control and treatment of risk sources. Even after the accident, the emergency handling of perturbations should be regarded as active prevention and control, because if it is not managed well, then it may lead to secondary accidents. In contrast, performance improvement strategies in the post-performance stage are passive recovery strategies that minimize losses through optimization algorithms, node management and control and other technologies under limited resource supply. To sum up, the impact of the former is more predictable and estimable, while the impact of the latter is difficult to predict and control. A broken transport network may isolate a community, and long-term recovery will worsen the situation. Therefore, researchers and practitioners today focused on making transportation networks resilient and less vulnerable to disasters, not just recovery activities ([Safapour and Kermanshachi, 2021](#)). Therefore, in the future application of CPS, it is suggested to focus on performance improvement strategies in the post-performance stage, supplemented by performance improvement strategies in the post-performance stage.

In the closed-loop CPS-T of traffic and information data, real-time dynamic regulation of bus transit becomes possible. Managers can adjust the resilience of bus fleets based on the status of the overall system network structure under abnormal perturbances, such as high-occupancy vehicle lanes implementation and bus headway holding. The mobility and convenience of bus transit can be fully used, enhancing resilience in terms of recovery in volume and speed from an extreme event.

The CPS offers a real-time, dynamic and closed-loop collaborative control environment for the resilience assessment of subway traffic. In the CPS-T, the subway traffic is no longer a closed and independent mode of transportation. The traffic data of multi-source perception can provide sufficient data for the resistance analysis of subway operation, which can accurately deduce the situation of disturbance impact, and then identify vulnerable nodes in the network. Moreover, the multi-mode bridging can come into effect under the closed-loop coordination mechanism. More transportation modes participate in resource allocation and scheduling, and the recovery time and repair efficiency of system resilience are improved.

5. Future trends and research direction

CPS is a more targeted solution to resilience issues in transportation. The cyber-physical advancements in sensors (e.g. vehicular probe) and the storage and processing of data (e.g. large-scale database) have made tracking a substantial flow of raw data possible, which is critical for CPS's actualization. The future trend of CPS in enhancing the resilience is predicted as follows:

- The theoretical framework of CPS will be substantially developed on the intersection of transportation and informatics.
- Both data and model will still drive the multi-modal modeling method on CPS's polymorphic migration features.
- Closed-loop control techniques for CPS's functional reconstitution will be based on the feedback of logic-physics interaction.
- The application of CPS on performance simulation and verification will follow a unique layered architecture from different functional modules to subsystems.

Four research directions can also be pointed out for the future resilience researchers as follows:

- (1) Under the current framework of multi-mode transportation resilience, the well-designed CPS could be one strategy to improve the resilience facing different perturbations. Because the CPS has advancing components such as modularized functional zones (prefabricated modules) that ensures the independence and integrity of every child element within each functional zone. Though the CPS requires the high development of advanced technology such as transportation informatics, parallel simulation and artificial intelligence, the best future form of CPS will be a heated issue to discuss.
- (2) Whether model-data hybrid simulation or other model-free methodology be the future research methodology that best fits the context of transportation resilience. All these methodologies have their advantages and drawbacks. Thus, if the hybrid methodology can precisely interpret the core mechanism of resilience, then a concrete combination needs further research.
- (3) Whether the new strategies for enhancing the resilience are going to come forth with the occurrence of new travel modes such as autonomous vehicles, because these new travel modes will dramatically reshape the transportation system, thus expanding the definition of transportation resilience. The innovative approaches to achieve a better resilience is worthy of our expectation.
- (4) How to assess and then enhance the transportation resilience in the context of an epidemic. Currently, the COVID-19 has a profound impact of transportation system. It is increasing the vulnerability on the network and threatening the health of commuters. One urgent task is developing a new assessment method of resilience during the epidemic (e.g. considering the spread of the virus as an indicator). Another urgent task is exploring new strategies for enhancing resilience, especially under the prolonged lockdowns. The new strategy should provide the necessary mobility while considering the safety of commuters.

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