Climate Change Impact Urban Transportation Resilience

Subjects: Geography, Physical
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Global warming, sea-level rise, and rapid urbanization all increase the risk of compound extreme weather events, presenting challenges for the operation of urban-related infrastructure, including transportation infrastructure. In this context, some questions become important.

Keywords: transportation resilience ; climate change ; weather events

1. Introduction

Global climate change will increase the occurrence of extreme weather events such as typhoons, storm surges, heavy rains, floods, high temperatures, heat waves, and droughts. The processes that cause these extreme weather events usually interact and depend on each other in space or time [1]. In recent decades, researchers have also witnessed compound events such as high-temperature heat waves, droughts, and typhoon storm surges with heavy rain and flooding [2]. Such instnces of two or more extreme weather events occuring simultaniously or successively are called extreme compound weather events. [3][4]. Compared with extreme weather events that occur in isolation, the damage to socioeconomic and ecological systems of such compound extreme weather events tends to be greater [5].

Global warming, rising sea levels, and rapid urbanization have made coastal cities vulnerable to heavy rains and floods, especially during typhoons and storm surges. The risks of compound extreme weather events (typhoon surges, heavy rainfall, and flooding) are increasing, severely challenging the operation of urban infrastructure [6]. Events such as Super Typhoon Meranti landed in Xiamen in 2016, Super Typhoon Mangkhut hit Guangzhou in 2018, and Super Typhoon Lekima struck in Taizhou in 2019. After these typhoons made landfall, they caused disasters such as storm surges, heavy rains, and floods, which damaged urban transportation infrastructure, blocked roads, and paralyzed bus lines [7][8][9]. This reveals the vulnerability of the transportation system to compound extreme weather events. In the next few decades, transportation infrastructure may face huge challenges due to climate change because these transportation systems have been designed for historical conditions and predictability [10].

UT resilience reflects the ability of the transportation system to maintain its basic functions and structure through its resistance, mitigation, and absorption under extreme conditions (such as public incidents, terrorist attacks, and natural disasters), called static resilience, or the ability to restore the original equilibrium or a new equilibrium state within a reasonable time and cost, called dynamic resilience [10][11]. Currently, there is, however, no reliable method that can accurately reveal the spatiotemporal evolution of UT resilience when subjected to compound extreme weather events and scientifically clarify the impact of global climate change (the frequency and intensity of extreme weather events caused by climate warming) on UT resilience. Therefore, reviews the existing research on UT resilience, summarizes the research progress on UT resilience, identifies the deficiencies in the existing research, and proposes the countermeasures for future complex extreme events under conditions of climate change. The recommendations on UT resilience research provide new ideas for future research.

2. Overview of Urban Transportation resilience Research

The research on UT resilience began in the 1970s [12], and the research on transportation system resilience has been steadily increasing since the 1990s. Based on transportation resilience papers published by Web of Science over the years (**Figure 1**), there has been a definite increase in the number of published papers, from a few in 2000 to 278 in 2020, and the percentage of publications has also jumped from less than 1% to about 25%, especially since 2010. From 2014 to 2020, research papers on transportation resilience showed explosive growth, which further reflects that with the deepening of research, the importance of transportation resilience is increasingly being recognized.

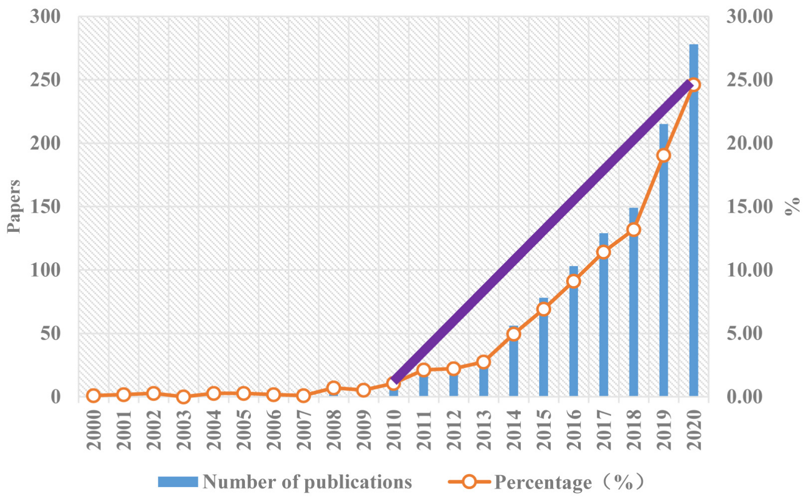

Figure 1. Time series distribution and percentage of transportation resilience-related research publications over the years. The purple trend line indicates the period of the rapid growth of research papers on transportation resilience.

The current research on UT resilience mainly focuses on conceptual frameworks, indicator systems, quantitative evaluations, and emergency and disaster response to extreme weather events and has achieved fruitful research results in related fields [10]. The above research involved the construction of a transportation resilience index system, analysis of the impact mechanism of extreme weather events on transportation resilience, exploration of the relationship between climate change and UT resilience, and the evaluation and prediction of the intensity of transportation resilience. The following is a description of the domestic and foreign research present situation from the above aspects.

2.1. Constructing the Transportation Resilience Index System

Urban transportation systems are always disturbed by extreme events such as natural disasters (typhoons, storm surges, heavy rains, floods) or man-made events (terrorist attacks, cultural incidents, strikes, and system failures caused by human mismanagement). The impact on urban transportation system functions may be the same as that of other urban system functions [13][14][15]. Due to the increased risk of extreme events in cities, the resilience of urban transportation systems has become the focus of transportation resilience [16][17]. The resilience of the transportation system not only refers to the ability to prevent the system from malfunctioning due to interference but also refers to the ability of the system to avoid, adapt to, and reduce the impact of catastrophic local events or the failure of the entire system [10]. During the construction of the transportation resilience-measurement system, it should be considered that the resilience of the transportation system should reflect the system's ability to mitigate the impact of extreme weather events and maintain its own functions. In addition, the time it takes for extreme weather events to disrupt the full function of the transportation system and the time it takes for the system to return to normal function should also be considered.

The indicator research on the definition of transportation resilience is a necessary step to construct a measurement system. Relevant research has adopted a series of concepts and definitions, which play a crucial role in the construction of the measurement system. The transportation resilience index system mainly includes the Redundancy, Adaptation, Efficiency, Robustness, Interdependence, Preparedness, Flexibility, and Rapidity of the system. Redundancy refers to the replaceable components of the system with the same function, such as the ability of certain components to take over the failed components without compromising the function of the system itself [18][19][20][21][22][23][24][25]. Adaptation refers to the system's ability to flexibly adjust its form, structure, or function according to changes in the external environment to deal with new pressures [25][26][27][28][29][30]. Efficiency refers to the ability to maintain the level of service and connectivity during an extreme event causing a system interruption [18][27][31][32][33]. Robustness refers to the ability of the system to resist and respond to external shocks [16][25][34][35][36][37][38][39][40][41][42][43][44]. Interdependence is the connectivity between system components, including the connectivity of the relational network between system components [45], while preparedness is the ability to prepare certain measures before the system is destroyed and to enhance the resilience of the system by reducing the potential negative effects of destructive events [22][29][46][47]. Flexibility refers to the ability of the system to respond to the impact of emergencies and adapt to changes through contingency plans after the system is interrupted. It is also called the ability to reconfigure resources to deal with uncertainties [16][19][23][34][39][45]. Rapidity is the ability of the system to achieve the goal of controlling losses promptly in accordance with priorities and avoiding future system outages [16][25][48][49]. Most of the above research only uses one or several of these concepts as the evaluation indicators of transportation resilience. Moreover, travel time and traffic flow (driving speed, etc.) are the main performance variables that reflect the above indicators, and they are also important measurement variables for changes in UT resilience under external and internal threats [10][50].

2.2. Analysis Mechanism of the Impact of Extreme Events on Transportation Resilience

Extreme weather events have many adverse effects on the transportation system, including high social, economic, and environmental costs [26]. Due to global climate change, extreme weather events occur more frequently than decades ago [51]. In this context, the ability of the transportation system to adapt to extreme weather becomes important [52]. **Table 1** shows the possible direct physical impacts of extreme weather events on transportation infrastructure.

Table 1. The possible direct physical impact of extreme weather events on transportation infrastructure (from [16]).

Types of Extreme Events	Impact on Transportation	Authors
Extreme heat events	Asphalt cracking Asphalt aging/oxidation Migration of liquid asphalt Asphalt softening rutting Railway bucking Catenary wire sag Failed expansion joints Concrete pavements blowups	[16][53][54][55]
Season shift in temperatures	Increased damage from freeze-thaw cycles More frequent landslides/mudslides	[16][56][57]
Extreme precipitation events	Flooding of roadways Overloading of drainage systems Roadway washout Bridge scour/washout Reduced structural integrity from soil moisture More frequent landslides/mudslides	[11][16][55][56][58][59][60]
Droughts	Greater chance of wildfire Road closure from wildfire & reduced visibility Increased flooding in a deforested area More debris in stormwater management systems Reduced pavement integrity due to ground shrinking	[16][55]
Sea Level Rise/Storm Surge/Coastal Flooding	More frequent/intense floods in low-lying areas Erosion of road base Erosion of bridge supports/bridge scouring Land subsidence	[11][16][55][57][59][60][61][62][63]

Currently, scholars study the damage and loss (quantitative and economic quantitative analysis), reliability, and vulnerability of urban transportation system facilities to various extreme events (earthquakes, tsunamis, typhoons, rainstorms, floods). Extreme events damage transportation infrastructure, impact commuting time and cost and cause road congestion, traffic accidents, and casualties [64][65][66][67][68][69]. Even though the abovementioned analysis is quantitative, it essentially only measures the vulnerability of the transportation system rather than its resilience [51]. Current transportation resilience research focuses on the impact of extreme events on traffic volume, mileage, punctuality, and driving costs, as well as the time required for the transportation system to return to equilibrium or the speed of recovery after extreme events [19][27][70][71].

2.3. Mining the Relationship between Climate Change and Transportation Resilience

The United Nations Intergovernmental Panel on Clime Change (IPCC) Fifth Assessment Report once again pointed out that over the past 100 years, the global climate system has experienced significant changes from global warming, which has increasingly affected human survival and development [72]. In the coming decades, transportation infrastructure (and other infrastructure systems) may face major challenges: they are largely unable to adapt to changes in external conditions and adjust their subsequent financial support, their use often far exceeds their expected lifespan, and they are becoming increasingly interconnected and complex [6]. The unstable changes of the global weather patterns due to climate change may exacerbate transportation infrastructure challenges (including aging, insufficient funding, historical conditions, and predictability), thereby seriously threatening the transportation infrastructure [55]. Although uncertain about the impact of future climate change, climate models indicate that extreme events and gradual changes in climate and hydrology may become more severe even under conservative scenarios, even with a significant reduction in greenhouse gas emissions in the short term [72][73]. Complicating this challenge is the inability to predict current or future conditions based on past trends [74]. Research has, however, been conducted on the robustness of the transportation system in response to climate change by strengthening its ability to adapt to climate change and other threats, and improving its control, prevention, and consolidation capabilities to prevent the destruction of transportation infrastructure [55][58][75]. A small number of scholars have also evaluated the impact of extreme weather events on UT resilience under the influence of climate change (the resilience recovery rate) and prediction studies and proposed standard indicators for the impact of climate change. These studies help researchers understand the influence of weather on transportation infrastructure and operations, how climate change will change the frequency and magnitude of these extreme events, and how synchronized technological and socioeconomic development may shape the future transportation network and improve or exacerbate the impact of climate change [76].

2.4. Evaluation and Prediction of Transportation Resilience Features

The analysis of the temporal and spatial evolution of UT resilience and intensity features relies on data sets with high precision, high resolution, and complete temporal and spatial coverage. Current research on the impact of extreme weather events on transportation resilience mainly focuses on the use of topological methods to quantify the resilience of the transportation system [77][78][79]. Topological resilience research usually simulates transportation resilience scenarios by continuously deleting nodes in the traffic network according to various scenarios in which extreme weather events occur and then measuring its resilience by the degree of node deletion for each scenario. Based on this research, it was found that the resilience of the transportation system can still be maintained at a high level when the traffic nodes are randomly deleted, but when the traffic nodes are deleted under specific extreme weather events, the resilience of the transportation system is reduced. Data-driven analysis is another important and effective method for studying UT resilience after extreme weather events. Big traffic travel data (such as taxi trajectory data and public transportation travel data) can be used through traditional statistical models, frame calculations, and emerging big data mining technologies to construct and evaluate internal threats based on urban traffic (such as traffic accidents and man-made technical failure) of the transportation resilience process. Analyzing the formation and development process of traffic resilience under the abovementioned specific events is currently common practice [20][30].

Recently, Deep Learning technology has shown great potential for predicting traffic resilience. It has performed well in transportation research because of its flexible model structure and powerful learning capabilities [80][81][82]. The recurrent neural network method has proved itself to be excellent in capturing long-term time dependence and has been widely used in daily traffic and transportation forecast analysis [81][82][83][84][85]. However, the recurrent neural network model ignores the proximity factors in the transportation system and cannot represent the spatial correlation. A convolutional neural network prediction model that can extract spatiotemporal features and consider the Euclidean space in grid structure data (such as images) is therefore proposed for prediction [86][87]. The traffic volume in the transportation system contains complex non-Euclidean and directional correlations and, at the same time, has stronger topological characteristics instead of general European space dependence. For this kind of spatial structure data, the original convolutional neural network method is not applicable. To solve the above problems, a graph convolutional neural network was developed to extend the convolution operator to any grid image. The graph of the convolutional neural network is applied to daily traffic predictions, such as the traffic speed in the traffic sensor network, the station-level demand in the shared bicycle network, and the real-time parking occupancy rate in the parking fee network, have achieved good results [88][89][90][91].

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