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Lessons From Climate and Pandemic-Induced Disruptions in Building Public Transport Resilience

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Abstract

The transport system faces numerous disturbances from climate change and other events, such as the Covid-19 pandemic. This study evaluates the resilience of public transport systems by applying the qualitative 4R framework—robustness, redundancy, resourcefulness, and rapidity—to four case studies drawn from the UK, South Africa, Mexico, and the United States. The analysis demonstrates that climate-induced disruptions predominantly expose infrastructural weaknesses and strain institutional capacity, while pandemic-related disruptions challenge the adaptability and operational flexibility of transport services. Notable findings include the critical role of early warning systems, the significance of sustained investment in resilient infrastructure—as evidenced in the UK and Mexico—and the detrimental impact of inadequate infrastructure maintenance, particularly in South Africa. The study advances recommendations for enhancing resilience, emphasising the adoption of integrated, multimodal transport systems, and reinforcing institutional coordination and planning capacity.

Keywords

climate change; Covid-19; public transport; resilience

1. Introduction

Climate change-induced disturbances have increased in occurrence and intensity over the last century. According to the IPCC Assessment Report, greenhouse gas emissions have continued to rise, resulting in global warming, with many regions across the world experiencing its effects (Ruane, 2024). Extreme weather events such as floods and hurricanes affect economic development and increase the vulnerability of people and systems. Particularly, the transportation infrastructure experiences damage, resulting in travel delays and loss of accessibility due to these events (Pan et al., 2021).

Several studies have examined the impacts of climate change disruptions on public transportation. The United States Environmental Protection Agency (2025) highlights how climate change can lead to flooding and extreme heat waves, thereby causing damage to roadways and rail links. Kafalenos et al. (2008) previously indicated that approximately 50–60% of roads and 30–40% of railway lines along the Gulf Coast region of the United States are susceptible to storm surges. Similarly, extremely low temperatures in the Netherlands have damaged railway infrastructure, leading to service delays (Xia et al., 2013). The case of Hurricane Sandy in New York is an example of how extensive flooding led to disruptions, subway service cancellations, and widespread road damage (Jing, 2021).

In terms of ridership, adverse weather conditions have been found to affect public transport usage negatively (Arana et al., 2014; Bo et al., 2021; Wu & Liao, 2020), often leading to a shift towards private vehicle usage, particularly in cities without subway systems (Böcker et al., 2019). High temperatures have been associated with passenger discomfort and possible changes in modes of transportation within the London underground (Arkell & Darch, 2006). In contrast, the effects of high temperatures on the Beijing subway ridership reveal a distinct pattern underscoring the complex relationship between transit usage and extreme weather conditions (Wu & Liao, 2020). Furthermore, extreme weather events have a more significant impact on leisure trips than commuting trips (Sabir, 2011).

The Covid-19 pandemic also affected public transportation usage. Studies highlight a shift from shared to private modes of transport, such as personal vehicles, due to safety concerns and the fear of contagion (Angell & Potoglou, 2022). This increase in the number of personal vehicles has led to environmental concerns, as research studies have indicated that private cars generate higher CO_2 emissions in comparison to public transportation (Acierto et al., 2023; Burchart-Korol & Folęga, 2019; Shang & Lv, 2023). Additionally, studies have highlighted a decrease in public transit ridership compared to pre-pandemic levels (Chen et al., 2024; Lee et al., 2024; Mepparambath et al., 2023; Srikanth et al., 2023; Stokenberga et al., 2023). Both climate change and the Covid-19 pandemic have had multifaceted impacts on public transportation systems, underscoring the need to strengthen the resilience of public transport.

Despite the growing body of literature examining the impacts of climate change and pandemic disruptions on public transportation, a critical gap remains concerning evaluating implemented resilience measures in response to these events. Much of the existing literature focuses on analysing the impacts of specific climate change events and travel behaviour shifts due to the Covid-19 pandemic. However, few studies, notably Amdal et al. (2017) and Fraser and Chester (2017), extend this analysis to assess actual adaptation strategies implemented to ensure resilience. Additionally, most of these studies focus on the Global North context, leaving a significant gap in understanding how these disruptions play out in the Global South context, thus limiting the ability to draw lessons from past interventions and develop context-specific resilient strategies.

This article aims to address these gaps by examining how public transportation systems have responded to challenges of climate change disruptions and the Covid-19 pandemic. Using selected case studies from both the global north and global south, the study focuses on identifying institutional and infrastructural lessons that inform resilient public transport planning and evaluating the effectiveness of these adaptive responses. A qualitative resilience framework is applied to assess how these adaptive measures enhance resilience. The article also highlights the challenges faced in implementing resilient measures and provides recommendations for creating a resilient public transportation system.

The remainder of the article follows this structure: Section 2 examines the literature on the concept of resilience, especially concerning transportation systems. Section 3 describes the methodology in detail, including the case study selection and data collection process. Section 4 presents and discusses the findings, focusing on the immediate response and long-term adaptive strategies employed during disruptions. Section 5 concludes the article by summarising key insights and offering recommendations for public transport resilience.

2. Literature Review

2.1. Defining and Assessing Resilience in Transport Systems

The concept of resilience was first introduced by Holling (1973) in ecological studies. Since then, the concept has been applied to other areas of study, such as psychology, economics, and engineering. Murray-Tuite (2006) was the first to define the resilience of transportation systems, categorising it into ten dimensions: redundancy, diversity, efficiency, adaptability, safety, mobility, autonomous components, strength, collaboration, and the ability to recover quickly. While these dimensions provide a measure of evaluating resilience, their complexity makes it difficult to establish a definite measure. Before this, Bruneau et al. (2003) proposed four dimensions of resilience: robustness, redundancy, resourcefulness, and rapidity. Tierney and Bruneau (2007) later named this the "R4 framework," which is extensively referenced in the literature. Robustness refers to the capacity of a system or its components to withstand disruption without incurring substantial functional degradation. Redundancy refers to the degree to which elements in a system are substitutable during a shock. Resourcefulness refers to the ability to recognise emerging problems, establish priorities, and allocate resources to address those problems. Finally, rapidity refers to the system's ability to respond promptly and efficiently to shocks, thereby minimising loss (Reggiani, 2013).

Building on these earlier definitions, the concept of resilience in transportation has been further developed and clearly defined. Based on a comprehensive literature review, Gonçalves and Ribeiro (2020, p. 3) proposed a definition of the resilience of urban transportation systems as the "ability for a system to resist, reduce, and absorb the impacts of a disturbance (shock, interruption, or disaster), maintaining an acceptable level of service (static resilience), and restoring regular and balanced operation within a reasonable period and cost (dynamic resilience)." This definition highlights two key aspects of resilience: static resilience, which pertains to the system's ability to maintain service during disturbances, and dynamic resilience, which focuses on recovery efficiency (Sun et al., 2020). Bruneau et al. (2003) describe a resilient system as one that demonstrates lower failure probabilities, minimised impacts when failure occurs, and shorter recovery time.

In terms of assessing and measuring resilience, several methods and approaches have been studied and developed, ranging from qualitative, semi-quantitative, and quantitative methods. Qualitative approaches evaluate transport resilience using attribute-based metrics such as the 4R framework. Hughes and Healy (2014) developed a qualitative framework for the New Zealand Transport Agency, incorporating measurement categories linked to two dimensions: technical resilience—encompassing robustness, redundancy, and safe-to-fail principles—and organisational resilience—comprising change readiness, networks, and leadership and culture. The measurement categories were associated with each principle. However, this framework was not tested in real-world scenarios. Similarly, the Los Angeles County Metropolitan Transit Authority (2015) proposed a resilience indicator framework based on similar principles.

Building on these, Tonn et al. (2020) assessed the resilience of the United States passenger rail within the Northeast corridor using a framework derived from the aforementioned studies, selecting 21 metrics and rating them on a scale of low, medium, and high.

Imran et al. (2014) proposed a framework incorporating six key variables—engineering, services, ecological, social, economic, and institutional—to evaluate transport resilience from a planning perspective. The proposed framework was applied to a case study in the Manawatu-Wanganui region of New Zealand. Kermanshachi et al. (2021) also identified 21 resilience metrics but focused on infrastructure project selection, developing a decision-support model to prioritise highly resilient projects. Additionally, Leobons et al. (2019) proposed 11 indicators based on the 4R properties and suggested methods to quantify each. Beldarrain et al. (2022) employed a qualitative approach through co-creative workshops and identified key factors that contribute to the resilience of public transport systems. These factors are categorised into system organisation, information management, operating performance, and subsystem integration.

Quantitative approaches have been extensively researched. Serulle (2011) developed a method of assessing resiliency using metrics such as average delay and reduction in network speed delays. Freckleton et al. (2012) carried out similar work. Other studies use topological metrics, which focus on network efficiency. The most used metrics are the giant connected component and the average shortest path (Zhou et al., 2019). Testa et al. (2015) used a combination of topological measures such as average degree, average shortest paths, betweenness centrality, clustering coefficient, and redundancy to estimate the level of resilience of the New York Metropolitan Area transportation system in the case of an extreme climate event. Aydin et al. (2018) proposed a framework for assessing the resilience of urban road networks by using the giant connected component as an indicator of robustness and betweenness centrality as an indicator of network efficiency.

Qualitative and quantitative approaches highlight the different methodologies available for assessing transportation resilience. While qualitative frameworks emphasise technical and organisational-based metrics, quantitative frameworks rely on performance-based metrics and network topology. The literature predominantly focuses on quantitative approaches, which offer detailed insights but often require extensive data. In contrast, qualitative methods are easily applicable and require less data.

2.2. Disruption Types and Their Significance to Transportation Resilience

Various disruptions impact transportation systems. These disruptions can be categorised into several types based on their nature. Table 1 shows the different categories of disruptions and examples of those disruptions. Some of these disruptions, such as those caused by nature, extreme weather events, and health pandemics, can be unexpected and difficult to predict.

Climate-related disruptions such as floods, heatwaves and severe storms are occurring more frequently, thus highlighting a need to plan for a more resilient infrastructure (Haggag et al., 2021). These disruptions often lead to structural damage, travel delays, inaccessibility, economic loss, injuries and death (Jenelius & Mattsson, 2020), and in many cases, public transport ridership is negatively affected (Bo et al., 2021; Tao et al., 2018). These disruptions amplify the existing vulnerabilities of public transport systems, especially in urban areas (Ji et al., 2022). Studies from developed regions highlight various resilience strategies. For instance, Kim et al. (2018) identify measures such as improved infrastructure design and maintenance,

Table 1. Types of disruptions.

Type of Disruption	Examples
Natural and Weather-Induced	Flooding, repetitive freezing and thawing, hurricanes, extreme heat, tornadoes, snow and ice, earthquakes, fires, landslides and avalanches
Synthetic and People-Induced	Demand surges, dynamic supply chain needs, criminal/terrorist activities, prolonged infrastructure use, rapid demographic movement, crashes, sea-level rise, heightened public involvement, health pandemics
Institutional	Asset management, funding instability, system exceeding capacity, ageing infrastructure, antiquated design, resource limitations, political risks, prioritisation
Economic	Technology disruption, trade and commerce instability, changing market conditions, transportation and logistic costs, environmental changes, eroding ecosystem, trade disputes, recession and depression

Source: Adapted from National Academies of Sciences, Engineering, and Medicine (2024a).

technological advancements, and enhanced communication systems. Similarly, Amdal et al. (2017) reviewed case studies, offering key lessons and structural and institutional measures to mitigate the impact of natural disasters on transit systems. However, these studies focus on developed regions with more substantial resources and institutional capacities than developing countries.

Conversely, the Covid-19 pandemic caused unprecedented disruptions to transportation systems, changing travel demand and operations due to restrictions (Lee et al., 2024). Public transport operators and agencies had to implement strategies to ensure the continuity of service. These included a decrease in fleet and frequency, as well as changes in service delivery (Lima et al., 2020; Zorgati et al., 2021). These interventions were often reactive, exposing gaps in planning (Tori et al., 2023). The Covid-19 pandemic exposed the need for adaptive governance and institutional coordination in enhancing system-wide resilience.

Both climate-induced and pandemic-induced disruptions impact different dimensions of public transport resilience. Climate-induced disruptions mainly affect infrastructure resilience, while pandemic-induced disruptions mainly affect the institutional aspect of resilience. Strengthening the resilience of public transport systems is therefore essential, requiring collaboration between institutions and end-users in developing resilience strategies (National Academies of Sciences, Engineering, and Medicine, 2024a).

In summary, drawing from the literature review, key gaps remain. First, most studies focused on natural, climate-induced disruptions or pandemic impacts in isolation, often within specific regions, thus lacking an integrated, cross-disruption perspective. Second, most studies use a quantitative approach to measure resilience, with limited attention to qualitative assessments incorporating technical and organisational dimensions. Third, limited studies compare responses across developed and developing nations or explore the integration of institutional, user, and technological factors, therefore limiting the adaptability of resilience strategies to different contexts.

This study addresses these gaps by adopting a comparative qualitative framework to analyse how diverse regions, across developed and developing contexts, respond to climate and pandemic disruptions. By examining four case studies, the article aims to identify lessons, evaluate responses, and contribute to a better understanding of public transport resilience.

3. Methodology

This study employs a qualitative approach, using a combination of document analysis, online news articles, and open-access public transport ridership data to investigate the resilience of public transport systems during extreme weather events and the Covid-19 pandemic. The methodology is outlined as follows.

3.1. Data Collection

Three primary types of data were collected: academic papers and policy documents, online news articles, and open-access transport ridership datasets. These sources were selected to capture the different dimensions of resilience and to triangulate information across various data types.

The documents were accessed through academic databases such as Google Scholar, ScienceDirect, the Transport Research Board publication database, and government and international agencies' websites. These databases were chosen due to their field-related relevance and accessibility. Google Scholar was employed due to its extensive coverage of scholarly articles across diverse academic fields, thereby capturing peer-reviewed articles on both pandemic and climate-related disruptions. ScienceDirect was utilised due to its strong focus on transportation, environmental science, and urban planning, thereby presenting articles focused on resilience and transportation. The Transport Research Board database was selected for its comprehensive collection of transport-related case studies, reports, and research articles, particularly within the context of the Global North, thereby providing valuable insights into adaptive resilience strategies. The synergetic use of these databases ensured a comprehensive assessment of resilience within public transport systems across various geographical regions, aligning with the study's overarching objectives.

The literature search was conducted using keywords such as *public transportation*, *resilience*, *climate change*, *extreme weather*, *pandemic*, *Covid-19*, and *adaptation*. The initial search yielded 200 articles. Afterwards, the documents were reviewed to understand the practical aspects of public transport resilience, adaptive strategies, and policies, and 131 articles were chosen for further review. The articles and reports were screened for relevance to public transport resilience, adaptation measures and strategies, and governance responses to climate and pandemic-induced disruptions. The inclusion criteria required that the documents directly address transport-related disruptions due to extreme weather events or the Covid-19 pandemic between 2019 and 2024 and provide insights into responses and adaptation measures. The exclusion criteria ruled out sources that lacked detailed insights or generalisation without evidence. Following these criteria, a total of 95 documents were included in the study.

The online news articles were sourced from regional and national news platforms using Google News and media archives. Targeted keywords included *storm disruptions*, *climate-change events*, *public transport disruptions*, and *Covid-19*. These articles were analysed to extract real-time accounts of weather-induced disruptions, their impacts on the transport sector, and the various responses towards recovery. Articles were selected if they provided specific details of the disruptions, including their effects on public transport and communities, and immediate responses by authorities. The inclusion of these media sources provided a local perspective and details not found in the literature.

Two open-access datasets were used for the trend analysis of ridership data:

1. The first dataset was from the American Public Transportation Association (n.d.), which contains transport ridership data in the United States for different modes of transport, including heavy rail, light rail, commuter rail, trolley bus, and commuter bus. The study selected to use the data on commuter rail and commuter bus since this data provides insights into the impact of the pandemic on public transportation, especially in a Global North context.
2. The second dataset was obtained from OECD Data Explorer and included data on the total distance travelled by public transport passengers in Mexico using different modes. The data extracted was from 2019 to 2023, which helped explore the pandemic's effects on public transport in Mexico, which is considered a country in the Global South.

The selection of these two datasets aimed to represent both the Global North and Global South contexts, thereby offering comparative insight. Limitations include differences in definitions between sources, which were acknowledged in the analysis. Contextual bias was mitigated by cross-referencing findings with literature and media sources and by situating each dataset in its context.

3.2. Case Study Selection

This article examines four case studies: Storm Babet in the UK; the April 2022 floods in KwaZulu-Natal (KZN), South Africa; and two pandemic-related cases concerning public transport ridership trends in Mexico and the United States. Storm Babet was one of the most severe storms that recently affected the UK, causing significant rail and road transportation disruptions. This case study provides a perspective on resilience from a developed context. The KZN floods were among the most devastating floods in South Africa, extensively damaging transportation infrastructure. This case provides an insight into resilience from a developing context. The pandemic-related cases in Mexico and the United States focus on public transport ridership and contribute to understanding how pandemic-induced demand shocks were managed from a developing and developed context.

Collectively, these four cases align closely with the research objectives by allowing the study to compare institutional capacity, infrastructure, and governance in both developed (the UK and the United States) and developing (Mexico and South Africa) contexts. Moreover, the combination of climate and pandemic-related disruptions facilitates an examination of how various shocks influence distinct dimensions of resilience. The aim is not to generalise findings but to identify patterns of resilience strategies that may be adapted or considered in other contexts.

The case studies were selected using the following criteria:

- Data availability: Accessibility to open reports, media documentation, and operational data, enabling a robust qualitative analysis of impacts, responses, and resilience strategies;
- Comparability: Selection of case studies that represent both developed and developing contexts, allowing for institutional and infrastructural comparison;
- Disruption occurrences: Case studies focused on recent disruptions from 2019 to date.

3.3. Data Analysis

The data analysis involved multiple methods to extract key insights from the data sources. A thematic analysis approach was used to classify reports and academic articles into themes of resilience, adaptive strategies and policy frameworks. This approach allowed for identifying recurring patterns and lessons from past disruptions. Similarly, the news articles were thematically organised to identify strategies and challenges faced by public transport authorities in responding to disruptions. The themes were developed inductively from the data sources, and iterative review and cross-referencing of the articles were used for validation to ensure consistency in interpretation. While thematic and content analysis are conceptually related, content analysis was used to extract specific details and to categorise the particular strategies, impacts, and challenges incorporated in the comparative framework detailed in Table 2.

Trend analysis was applied to the study of the public transport data to compare ridership before, during, and after the pandemic. The objective was to identify ridership patterns, thus highlighting the impact of the pandemic on public transport usage. The data was analysed using descriptive statistics and was plotted over time to show peaks, troughs, and recovery trajectories. The observed trends were linked to the institutional responses identified in the literature sources.

A structured comparative analytical framework was developed based on the 4R resilience model, incorporating metrics adapted from Hughes and Healy (2014) and the Colorado Department of Transportation (n.d.). As presented in Table 2, this analytical framework was systematically applied to the selected case studies. Each case was assigned a qualitative resilience score as outlined in the clearly defined criteria below:

- Very high resilience: All requirements met (i.e robustness, redundancy, resourcefulness, rapidity, all met satisfactorily);
- High resilience: Acceptable performance, but improvements could be made;
- Moderate resilience: Less than desirable performance. Priority to be given to some improvements;
- Low resilience: Poor performance. Major improvements are required.

Table 2. Comparative analytical framework.

Resilience Principle	Qualitative Indicator: Climate-Induced Disruption	Qualitative Indicator: Pandemic-Induced Disruption
Robustness	Structural integrity of transport infrastructure, maintenance history	Physical infrastructure adaptability to reduced capacity
Redundancy	Availability of alternative routes, services or transport modes that can function during disruption	Availability of other mobility options (i.e., micro-mobility)
Resourcefulness	Institutional capacity: mobilisation of funds, emergency responses, early warnings, communication, relief	Scope of service redesigns and infrastructure development, mobilisation of funds
Rapidity	Time taken to clear and restore critical transport links, speed of response and decision making	Time taken for recovery of service (i.e., ridership recovery), speed of implementing decisions

While scoring resilience can introduce some subjectivity, the criteria were defined consistently, and each score is based on the documented data. This framework serves as a comparative lens rather than an absolute measure.

The combined use of these methods supports the study's aim of uncovering context-specific resilience strategies and institutional responses, contributing to a better understanding of how public transport systems adapt when faced with climate-related events and pandemic-induced disruptions.

4. Results and Discussion

This section presents the findings from case studies, analysing the impacts of climate-induced and pandemic-induced disruptions and discussing the resilience demonstrated in each case. The analysis incorporates the 4R framework (robustness, redundancy, resourcefulness, and rapidity) to rigorously assess the measures implemented, evaluate their effectiveness, and compare impacts across different contexts. The recurring patterns in disruptions, institutional responses, and lessons learned were discussed and summarised.

4.1. Resilience Assessment

Using the qualitative analysis framework developed, the case studies can be comparatively analysed, capturing the institutional and infrastructural dimensions of resilience across diverse contexts (see Table 3). Each case study's observed measures and outcomes were discussed and categorised below.

Table 3. Comparative analytical framework for assessing resilience.

Case Study	Robustness	Redundancy	Resourcefulness	Rapidity	Score
Storm Babet (UK)	Damage to roads and rail in some areas illustrated some vulnerability to flooding Emergency preparedness	Rail service cancellation indicates a lack of redundancy in that mode Some alternate routes were available	High resourcefulness in mobilising emergency services, funds for repairs and issuing early warnings Investment in long-term resilience shows high resourcefulness	Rapidity in issuing early warnings and responding to disruptions immediately Recovery of transportation infrastructure varied	High Resilience
KZN Floods (South Africa)	Infrastructure is highly vulnerable to flooding Poor maintenance of the drainage infrastructure contributed to a lack of robustness	Limited redundancy, as some communities became inaccessible	Resourcefulness in providing humanitarian relief Resourcefulness at the community level Limited capacity to conduct rapid damage and repairs	Slow initial response, assessment of damage and recovery Long-term plans for climate change adaptation indicate a focus on rapidity	Low Resilience

Table 3. (Cont.) Comparative analytical framework for assessing resilience.

Case Study	Robustness	Redundancy	Resourcefulness	Rapidity	Score
Covid-19 (United States)	Ridership decline indicates vulnerability, but the system can maintain some service	Service extension and micro-mobility integration ensured redundancy	Resourcefulness in implementing strategies to increase ridership	Rapid response in implementing strategies Gradual recovery of ridership	High Resilience
Covid-19 (Mexico)	Ridership decline indicates some vulnerability, but the system can maintain service	Route expansion and bus rapid transit (BRT) development increased redundancy	Resourcefulness in providing funding, subsidies and tax exemption, as well as infrastructure development	Rapid recovery of bus ridership, but rail is slowly recovering	Moderate Resilience

The following sections provide a more detailed discussion of the resilience demonstrated in each case, drawing on the 4R framework and expanding on the information provided in Table 3. The recurring patterns, like disruptions, institutional responses, and lessons learned, were discussed and summarised in Table 4.

4.2. Climate-Induced Disruptions

4.2.1. Case Study of Storm Babet in the UK

In late October 2023, Storm Babet struck the UK, causing significant disruptions, including power outages, flooding homes and roads, and travel delays due to road closures (Internet Geography, n.d.). Rail services and ferries were cancelled, and Leeds Bradford Airport was temporarily closed on 20 October (Calder, 2023). The cost of repairs in Scotland alone was estimated at £4 million (Watt, 2024). Figure 1 illustrates some of the damages to the transport infrastructure.

The initial response to Storm Babet demonstrated a degree of robustness in the form of emergency preparedness. The issuance of early weather warnings and the deployment of sandbags and pumps by the Environment Agency (2023) showcased a proactive approach to mitigating the immediate impacts. The early warning systems were effective in safeguarding public safety and facilitating evacuations (Internet

Figure 1. Damage to train lines. Sources: (a) Network Rail in Stefani (2023); (b) "Flood-hit residents 'won't be home for Christmas'" (2023).

Geography, n.d.) and the sandbags and pumps protected approximately 96,000 properties. The availability of such resources, as well as a flood resilience scheme for affected property owners (Engage Environment Agency, n.d.), indicated a level of resourcefulness in responding to the crisis.

The rapidity of recovery varied across transport modes. Rail service providers worked earnestly to remove debris and repair damages to resume service as quickly as possible (KITE Projects, 2023). Interim repairs were done to some affected roads, allowing for the resumption of traffic flow; though, some severely damaged roads remained closed (English, 2023; Ward, 2023), hence suggesting a need for improvement in addressing critical infrastructural failures.

In terms of long-term recovery and adaptation, infrastructure investment into drainage works, winter readiness programmes, flood risk alleviation, and integrated transport schemes has been implemented in different counties ("Nottinghamshire: Highways update shows record £66m investment," 2025; Suffolk County Council, 2023). These efforts focus on enhancing robustness and improving the infrastructure capacity to withstand future disruptions. Additionally, the UK Government awarded £1.4 million in projects that focus on developing resilient infrastructure (UK Research and Innovation, 2023). To ensure resilience in rail services, Network Rail, which oversees rail services in the UK, planned to invest £1.274 billion in the maintenance and renewal of earthworks and drainage, intelligent infrastructure, which includes remote monitoring and sensing, and research and innovative solutions (Haines, 2021). These long-term investments further demonstrate a commitment to building long-term robustness and redundancy into the transportation system and support the "High Resilience" score in Table 3.

4.2.2. Case Study of the KZN April 2022 Floods

In April 2022, heavy rainfall in the KZN coastal region, including Durban and the South Coast, resulted in severe flooding that led to fatalities, property damage, and destruction of infrastructure, such as roads, bridges, powerlines, and pipes (Thoithi et al., 2022). Figure 2 shows some of the damage to the road infrastructure. Poor maintenance of the drainage infrastructure and inadequate regulation of informal settlements exacerbated the flood impacts (Hattingh, 2022). The cost of repair was estimated to be around

Figure 2. Damage to roads due to April 2022 floods in KZN. Source: Darren Stewart in Buthelezi (2022).

R17 billion (Monama, 2022). The damage to roads and bridges resulted in the transport infrastructure leaving 60% of communities inaccessible by roads (Magubane, 2023).

The immediate response to the flood included the establishment of shelters, the provision of humanitarian relief to the affected families, and an emergency relief fund (Mudefi, 2023). However, damage assessment and repairs were delayed due to a lack of capacity (Maluleke, 2022), thus hindering rapid recovery. This lack of capacity resulted in some residents repairing the damaged roads and bridges to restore accessibility (Enoch, 2022), demonstrating a degree of community resourcefulness in the face of institutional delayed action.

Traffic on some damaged roads was managed through deviations or reopened after risk assessments and interim repairs, with permanent repairs planned for the third quarter of 2022 (Department of Planning, Monitoring and Evaluation, 2023); however, the overall recovery process was slow. The availability of alternate routes for traffic diversion shows a level of redundancy, but this is limited since some communities were left inaccessible. Long-term adaptation efforts included promoting climate change awareness, improving access to early weather warnings, and encouraging municipalities to develop climate change response plans (Department of Economic Development, Tourism and Environmental Affairs, 2023), thereby improving the region's adaptive capacity and preparedness. Overall, the case illustrates low resilience due to infrastructural vulnerability, making it susceptible to the impacts of the disruption and institutional capacity constraints, which led to delayed response and recovery.

4.3. Pandemic-Induced Disruptions

4.3.1. Case Study of Public Transport Ridership in the United States

Figure 3 shows the commuter rail and bus ridership trends in the United States from 2014 to 2023. As indicated, ridership declined sharply during 2020 due to the Covid-19 pandemic, with a gradual recovery afterwards, though ridership levels remain lower than the pre-pandemic levels. The decline in ridership led to financial losses and a reduction in service levels (Federal Transit Administration, 2024). This decline indicates an initial lack of robustness in the face of the pandemic.

However, some service providers implemented strategies to boost ridership amidst the pandemic, which proved successful. These strategies included service extensions, new rail stations and bus services connecting to the rail stations, bus route extension and redesign, transit signal priority and bus lanes, exclusive bus-only roads, micro-mobility services, investment in new technologies such as Wi-Fi on buses and ticket vending machines, discounts for bike sharing riders and BRT, like features such as queue jumpers and enhanced stops, free fare zones, and many other interventions (Tabassum et al., 2024). These measures represent a significant adaptation of service provision in response to the disruption, illustrating resourcefulness in identifying and implementing solutions. The quick integration of micro-mobility services and extending operations enhances redundancy.

According to the American Public Transportation Association (2021), leveraging such opportunities and institutionalising the best practices from the pandemic period will ensure the resilience of public transit in the post-pandemic period alongside prioritising social equity. The free-fare strategy has been one of the interventions adapted for post-pandemic implementation, with the National Academies of Sciences,

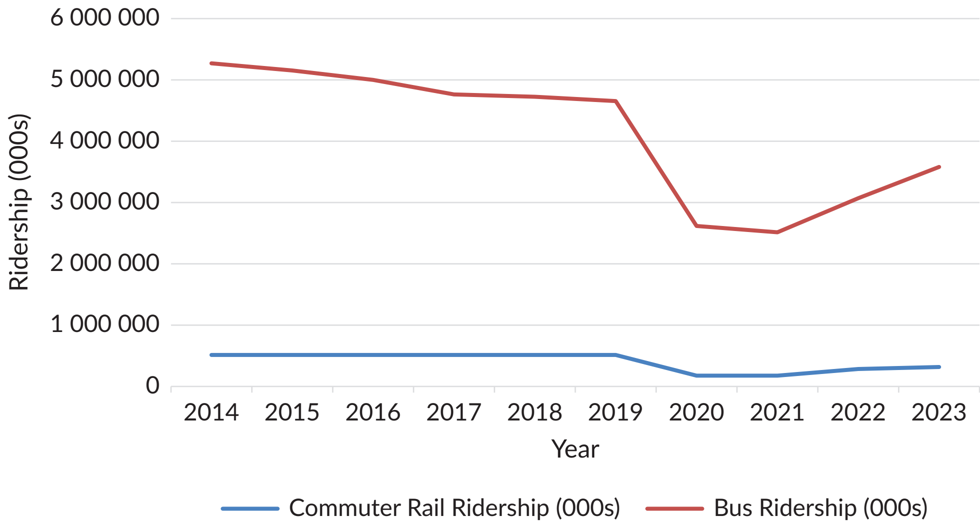

Figure 3. Year-end ridership by mode in the United States.

Engineering, and Medicine (2024b) published guidelines to support state departments of transportation and transit agencies in adopting these strategies. While ridership is recovering, it is still below pre-pandemic levels, indicating that full recovery is ongoing and that rapid return to pre-pandemic levels is variable. The prompt carrying out of recovery plans and rapid adaptability demonstrate high resilience.

4.3.2. Case Study of Public Transport Ridership in Mexico

Figure 4 shows the annual passenger kilometres by bus in Mexico from 2019 to 2023, indicating a significant decline in 2020 due to the pandemic, followed by a strong, rapid recovery in the subsequent years, suggesting a high resilience in this transport mode. In Mexico City, microbuses, which form a core part of the public transportation system, expanded their routes during the pandemic to provide services to peripheral areas (Calnek-Sugin & Heeckt, 2020), indicating resourcefulness and enhancing redundancy within the system.

The rail passenger kilometres, as shown in Figure 5, decreased during the pandemic and had a slow recovery thereafter, compared to the bus sector. This highlights different levels of resilience within different modes of

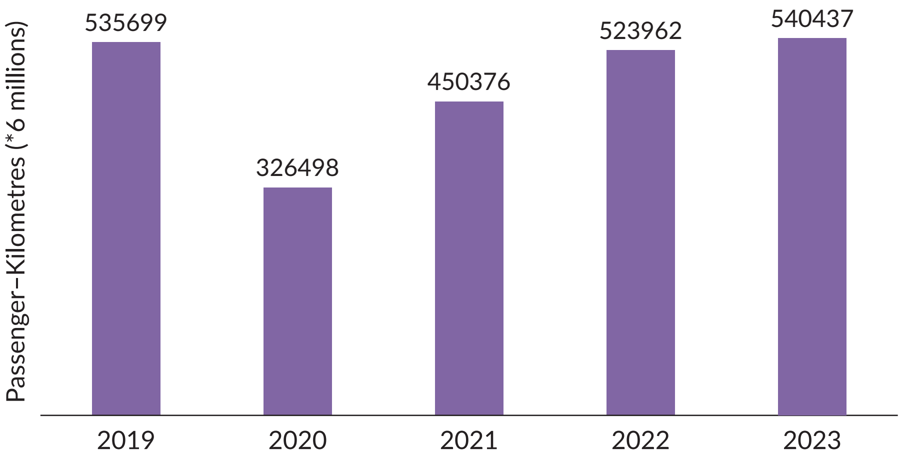

Figure 4. Bus passenger-kilometres in Mexico.

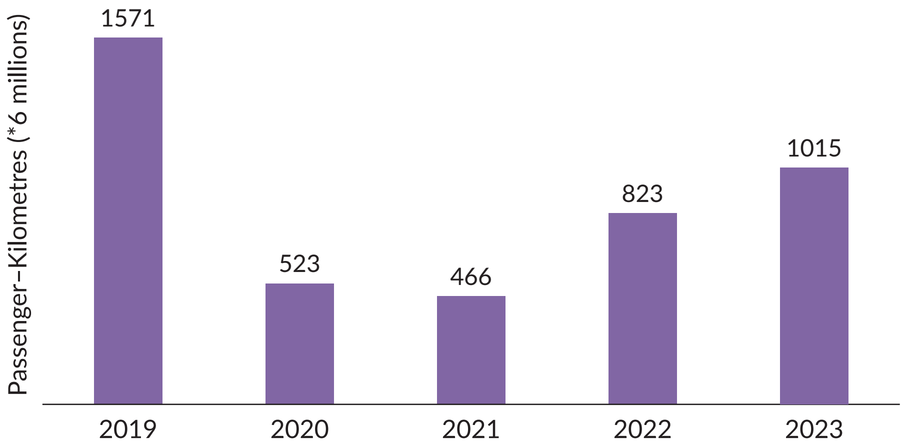

Figure 5. Rail passenger-kilometres in Mexico.

transport. To foster recovery, fuel subsidies and local tax exemptions were granted for some time to support the public transport services (World Bank, 2024). Additionally, new BRT infrastructure was constructed, transforming a car-oriented corridor in Guadalajara into a dedicated BRT route (Welle et al., 2023), thus improving redundancy. The Mexican government has also approved funding of US$7.6 billion to enhance passenger and freight rail services (Briginshaw, 2024). These investments represent resourcefulness and aim to improve the system's redundancy and robustness. While the response was generally prompt, the variation in modal recovery highlights the need for improvement in institutional alignment to enhance overall resilience, hence the moderate resilience score.

Table 4. Comparative summary of findings.

Patterns	Storm Babet (UK)	KZN Floods (South Africa)	Covid-19 (United States)	Covid-19 (Mexico)
Nature of Disruption	Severe storms and flooding	Intense flooding	Public health crisis	Public health crisis
Extent of the Disruption	Transport delays, rail service closures, and infrastructure damage	Infrastructure damage (major roads and bridges) and communities are inaccessible	Sharp drop in public transport usage	Ridership decline
Interventions	Early warnings, emergency repairs, and resilience funding	Shelters, humanitarian aid, and slow emergency repairs	Micro-mobility, fare reform, service redesign	BRT construction, subsidies, and tax relief
Effectiveness of Interventions	Timely warning and partial repairs were adequate, as rail service was restored	Recovery was slow, therefore revealing limited institutional capacity	Moderate ridership recovery as recovery measures were implemented quickly	Effective in the bus sector as ridership recovered, not so much in rail
Lessons Learned	Importance of flood planning, proactive action and funding	Need for infrastructure maintenance and rapid institutional action	Value of innovation and rapid institutional action	Value of innovation, investment and ode specific transport planning

4.4. Discussion

The case studies reveal differences and similarities in how public transport systems respond to climate- and pandemic-induced disruptions. Both types of disruptions led to significant reductions in transport service usage, although the nature of the disruption varied. Climate events caused physical damage to infrastructure, while the pandemic primarily affected demand. This distinction reflects the difference between soft (behavioural, institutional, and policy-based) and hard (infrastructure-based) components of the transport system (Chan & Schofer, 2016; Omer et al., 2014). The responses to climate events focused on providing disaster relief, infrastructure repair, and long-term adaptation measures, whereas the pandemic responses involved service adjustments and financial support to service operators.

Regarding cross-case analysis of climate-induced disruptions, the UK and KZN demonstrated different challenges and responses. The UK's experience with Storm Babet showed the importance of robustness through early warning systems and infrastructure investments, as well as rapidity in response, as summarised in Table 4, which is consistent with the recommendations by Rogers and Tsirkunov (2010) that early warning systems coupled with investment in infrastructure would enhance resilience. Pregnolato and Dawson (2018) also recommend infrastructure investment as a key component to enhance the resilience of transport infrastructure.

In contrast, the KZN floods exposed vulnerabilities related to infrastructure maintenance and rapidity in emergency response and infrastructure repairs. These findings align with a previous study by Revi et al. (2014), which highlighted the lack of consideration of climate change in the transportation sector in the Durban region of KZN, thus making it vulnerable to climate-related impacts. Satterthwaite et al. (2020) also highlighted the impact of socio-economic vulnerability and governance shortfall in the Global South regions, which impede resilience. Both cases highlight the need for long-term adaptation. Still, the KZN case shows the importance of addressing underlying socio-economic factors to improve the overall resilience of the transport system.

Comparing the United States and Mexico cases, we see that both countries experienced a sharp decline in public transport use. However, the rapidity of recovery differed. Mexico's bus system recovered rapidly compared to the United States. This could be attributed to socio-economic differences, policy responses, and the structural attributes of the system, as there was a focus on microbus route expansion and construction of a BRT route, which supports redundancy (Jenelius & Cats, 2015). Similarly, the United States focused on service extension, route expansion, micromobility services, and technological advancements. While direct quantitative comparison is limited, the analysis reveals insights into factors influencing resilience.

The comparative analysis highlighted the impact of disruption type on resilience performance and the varying adaptation capabilities of different national contexts. A summary of the implications of each climate-induced disruption tends to expose the physical vulnerabilities of transport infrastructure and challenge institutional capacity for rapid response. In contrast, pandemic-induced disruptions emphasise operational flexibility, innovation, and policy adaptation. Ultimately, the 4R framework reveals that resilience depends not only on robust infrastructure but also on governance structures, preparedness strategies, and innovation.

4.5. Summary of Key Lessons

- *Importance of Early Warning Systems*: Early warning systems are critical in minimising the impact of disruptions. The UK's effective release of emergency warnings and timely deployment of sandbags successfully safeguarded lives and infrastructure. In contrast, South Africa's lack of such systems and delayed response highlights the need for institutional frameworks to implement early action plans.
- *Resource Capacity*: Adequate financial and human resources are necessary to ensure the timely response and recovery of transportation systems and infrastructure. South Africa faced challenges in conducting an early risk assessment due to limited capacity, resulting in recovery delays, thereby forcing community-led restorative efforts. On the other hand, the UK, United States, and Mexico could quickly respond and adapt due to well-resourced agencies.
- *Long-Term Investments in Resilient Infrastructure*: Investment in resilient infrastructure is a priority. The UK focused on improving the drainage infrastructure, alleviating flood risk, and building intelligent infrastructure. Similarly, the United States and Mexico invested in innovative approaches such as redesigning transit routes and expanding BRT infrastructure. Despite resource constraints, South Africa also aimed to address structural vulnerabilities.
- *Adaptation Through Innovation*: Innovative approaches adopted by the United States, including the free-fare strategy, redesign of bus routes, micro-mobility services and technological enhancements, and the UK's investment in remote monitoring and sensing, illustrate the potential for innovation to support recovery and resilience in public transport systems.

5. Conclusion and Recommendations

Building resilience in public transportation systems is critical to addressing the increasing threats posed by climate-induced disruptions and global health crises. This study highlights the importance of proactive planning, infrastructure investment, and adaptive strategies to mitigate the impacts of such challenges. Case studies from developed and developing nations demonstrate that resilience requires a multifaceted approach, encompassing physical infrastructure improvements, institutional preparedness, and user-focused measures.

Key findings emphasise the need for investment in integrated transport infrastructure that can withstand and adapt to shocks, including multimodal networks and service expansions. Furthermore, institutional capacity strengthening is necessary through robust early warning systems, leveraging innovative solutions such as remote sensing, digitisation, and inter-agency coordination. Additionally, there is a need to prioritise the maintenance of existing infrastructure to reduce vulnerability.

This study underscores the necessity of a comprehensive and inclusive approach to resilience, offering actionable strategies to strengthen public transportation systems. However, transport systems are influenced by social, political, and spatial structures. Therefore, the findings of this study should be interpreted with caution, as the cases presented reflect diverse contexts. Rather than offering global solutions, the findings of this study offer insights into resilience-building that can inform context-specific strategies. The limitations of this study include the dependence on secondary data, which might omit undocumented resilience measures. Furthermore, the qualitative assessment framework applied is subjective and depends on the availability and consistency of the data. Moreover, using the case study approach limits the generalisation of the study's findings. It introduces a certain level of bias, which may fail to comprehensively cover the topic of public transport resilience across different regions.

Future research should focus on conducting more local case studies based on primary data to capture the actual experiences of the disruptions, developing a standardised resilience metric that can be applied across different contexts while ensuring local relevance and examining the resilience of informal public transport systems to these disruptions, especially in developing regions, which are rarely reported.

Ultimately, this study offers insight into the resilience of public transport systems, emphasising the need for inclusive, context-specific approaches. Adapting the lessons from this study will be essential in enabling the adaptability and recovery of public transport systems in the event of a disruption.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability

The data are available on request from the KZNDoT Chair in Sustainable Transportation at the University of KwaZulu-Natal and the authors.

LLMs Disclosure

None.

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