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REVIEW

Insights Gained from Weather Extremes and Health Crises in Strengthening Mass Transit Durability

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ABSTRACT

Mobility networks worldwide face escalating challenges from climate-induced environmental shifts and major disruptions such as the global COVID-19 pandemic. This scoping review investigates the resilience of public transport systems through a structured 4R framework—robustness (strength), redundancy (alternatives), resourcefulness (ingenuity), and rapidity (speed). The analysis draws on four diverse regional cases from Britain, Southern Africa, Central America, and North America to provide comparative insights. The article reveals that weather-related interruptions, including floods, storms, and extreme temperatures, predominantly expose structural weaknesses in infrastructure and place significant strain on administrative and operational capacities. In contrast, pandemic-related disruptions primarily test the adaptability and functional agility of transport services, highlighting the need for flexible operational models and rapid response capabilities. Key findings underscore the critical role of effective early warning and alert mechanisms in mitigating risks. Sustained investment in resilient infrastructure has proven valuable, as demonstrated by proactive approaches in Britain and Central America. Conversely, chronic under-maintenance and funding shortages have severely undermined system performance, particularly in Southern Africa. The study proposes practical strategies to enhance resilience, emphasizing the development of integrated and diversified mobility networks that combine public transport with active and shared modes. It also stresses the importance of strengthening inter-

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agency collaboration, governance structures, and preparedness planning to better equip transport systems for future uncertainties.

Keywords: Environmental Shifts; Health Outbreak; Communal Transit; Durability

1. Introduction

Environmental shift-triggered incidents have grown in frequency and severity during the past hundred years. Per the global climate panel's evaluation, pollutant releases have kept increasing, causing planetary heating, with numerous areas worldwide feeling the consequences [1,2]. Intense climatic occurrences like inundations and tempests influence financial growth and heighten the susceptibility of individuals and setups. Specifically, mobility structures suffer harm, leading to journey postponements and reduced accessibility from these happenings [3,4].

Multiple investigations have explored the effects of environmental shifts on shared mobility. The United States Environmental Protection Agency points out how such changes may cause floods and severe heat periods, thus harming roads and track connections. Earlier, about half to three-fifths of roads and a third to two-fifths of rail lines near the southern coastal area of North America were prone to wave surges. Likewise, very cold conditions in a European nation have injured track structures, resulting in operation lags [5,6]. The instance of a major storm in a large city demonstrates how broad floods caused halts, underground cancellations, and extensive path destruction [7,8].

Regarding passenger numbers, unfavorable climatic states have been observed to decrease shared transit utilization [5], frequently causing a move to individual cars, particularly in urban centers lacking underground lines [6]. Elevated heat has been linked to rider unease and potential switches in travel methods in an underground system [9]. Conversely, the influence of warmth on underground usage in an Asian metropolis shows a unique trend emphasizing the intricate link between mobility choices and harsh climates [8]. Moreover, severe climatic events affect recreational journeys more than daily commutes [9,10].

The health crisis also impacted shared mobility usage. Review indicates a transition from collective to personal travel options, like private cars, because of health worries and infection fears [10]. This rise in individual vehicles has raised ecological issues, as investigations show that personal automobiles produce more pollutants than communal options [11]. Further, studies have noted a drop in shared mobility passenger counts relative to before the crisis [12]. Both environmental changes and the health emergency have had diverse influences on shared mobility setups, highlighting the necessity to bolster their durability.

Even with the expanding collection of studies reviewing the influences of environmental shifts and crisis interruptions on shared mobility, a major shortfall persists in appraising applied durability actions responding to these occurrences. A lot of current work concentrates on examining the effects of particular environmental incidents and alterations in journey habits during a health emergency. Yet, only a few investigations have broadened this review to evaluate real adjustment tactics used to guarantee durability [11,12]. Also, most of these works center on advanced nations, creating a notable void in comprehending how these interruptions occur in emerging areas, thereby restricting the capacity to learn from prior actions and create tailored durable tactics.

This review article seeks to fill these voids by investigating how shared mobility setups have reacted to difficulties from environmental shift interruptions and the health crisis. Employing chosen examples from advanced and emerging regions, the review emphasizes spotting administrative and structural insights that guide durable shared transit preparation and assessing the success of these adjustment reactions. A descriptive durability model is used to evaluate how these adjustment steps improve durability. The piece also points out the obstacles encountered in applying durable actions and offers suggestions for developing a sturdy shared mobility setup.

The rest of the piece is organized like this: Section 2 reviews the work on the idea of durability, particularly regarding mobility setups. Section 3 explains the approach thoroughly, including example choice and information gathering method. Section 4 shows and reviews the observations, concentrating on instant reaction and extended adjustment tactics used during interruptions. Section 5 wraps up the piece by outlining main understandings and providing suggestions for shared transit durability.

This paper integrates insights from selected international case studies and peer-reviewed literature to examine how extreme weather events and public health crises have affected urban transit systems through the lens of the 4R resilience framework. The contribution of this study lies in its comparative synthesis of documented experiences and lessons learned, providing policy-relevant insights rather than statistically generalizable conclusions. This article is structured as a scoping review that synthesizes peer-reviewed and high-quality institutional literature on public transport resilience to extreme weather events and public health crises. The study maps existing evidence, analytical approaches, and response patterns across heterogeneous cases rather than generating new empirical data. Consequently, conclusions are framed as context-dependent insights and research directions rather than statistically generalizable findings.

2. Literature Review

2.1. Explaining and Evaluating Durability in Mobility Setups

This scoping review covers literature published between 2010 and 2024. Sources were identified from three categories:

(i) Academic databases (Scopus, Web of Science, Google Scholar) to capture peer-reviewed research;

(ii) Institutional and policy reports (e.g., World Bank, Union Internationale des Transports Publics (UITP) (International Association of Public Transport), American Public Transportation Association (APTA)) to document operational and governance responses; and

(iii) Grey literature (official agency releases and reputable media) is used only to contextualize event timelines and impacts.

The notion of durability originated with Bruneau et al. [13] and Burchart-Korol and Folęga [14] in natural system review. Afterward, the idea has been utilized in other fields, like mental health, finance, and construction. Buthelezi [15] and Calder [16] first explained durability in mobility setups, grouping it into ten aspects: alternatives, variety, productivity, versatility, protection, movement, independent parts, power, teamwork, and quick restoration ability. Although these aspects offer a way to assess durability, their intricacy complicates creating a clear gauge. Prior, Calder [16] suggested four aspects of durability: strength, alternatives, ingenuity, and speed. Calnek-Sugin et al. [17] and Enoch [18] subsequently called this the "4R model," which is widely cited in studies. This review adopts the 4R framework, mapping the dimensions as:

- Robustness (strength)—Robustness refers to the ability of physical assets to withstand disruption;
- Redundancy (alternatives)—Availability of substitutable elements/routes/modes;
- Resourcefulness (ingenuity)—Capacity to mobilize resources, adapt, and prioritize;
- Rapidity (speed)—Timeliness of response and recovery.

Redundancy denotes the availability of alternative routes or modes; resourcefulness captures institutional capacity to mobilize resources and coordinate responses; and rapidity reflects the speed of service recovery.

Strength means the ability of a setup or its elements to endure interruption without major operational drop. Alternatives mean the level to which parts in a setup can replace each other during a crisis. Ingenuity means the skill to spot arising issues, set orders, and assign assets to handle those issues. Lastly, speed means the setup's skill to react quickly and productively to crises, thus reducing damage [18].

Expanding on these prior explanations, the notion of durability in mobility has advanced and been precisely outlined. From a thorough work review, Chen et al. [19] and the Colorado Department of Transportation [20] suggested an explanation of urban mobility setup durability as the "skill for a setup to oppose, lessen, and take in the effects of an interruption (crisis, halt, or calamity), keeping a suitable service degree (fixed durability), and returning to normal and stable function in a fair time and expense (active durability)." This explanation stresses two main parts of durability: fixed durability, relating to the setup's skill to sustain service amid interruptions, and active durability, centering on restoration productivity [20]. It portrays a durable setup as one showing reduced breakdown chances, lessened effects when breakdown happens, and briefer restoration period.

Regarding evaluating and gauging durability, various ways and methods have been examined and created, spanning descriptive, partly numerical, and numerical methods. Descriptive methods assess mobility durability using feature-based gauges like the 4R model. KwaZulu-Natal Province [21] created a descriptive model for a transport body, including gauge groups connected to two aspects: technical durability—including strength, alternatives, and fail-safe ideas—and administrative durability—including readiness for shifts, connections, and guidance and ethos. The gauge groups were linked to each idea. But, this model was not checked in actual situations. Expanding on these, the Department of Planning, Monitoring and Evaluation [22] evaluated the durability of North American traveler rail lines in a northern corridor, using a model from the prior studies, picking 21 gauges and scoring them as poor, average, and strong.

Researchers suggested a model including six main factors—construction, options, natural, community, financial, and administrative—to assess mobility durability from a preparation viewpoint [23,24]. The suggested model was used in an example in a New Zealand area. Researchers also spotted durability gauges but centered on structure project choice, creating a choice-aid model to rank very durable projects [25,26]. Moreover, researchers suggested signs based on the 4R traits and proposed ways to measure each, used a descriptive method via joint workshops, and spotted main factors adding to the durability of shared transit setups [27–29]. These factors are grouped into setup arrangement, data handling, functional output, and subsystem connection.

Numerical methods have been broadly studied. Freckleton et al. [30] created a way of evaluating durability using gauges like average lag and drop in network pace lags comparable to work. Other studies use structural gauges, centering on network productivity. The most utilized gauges are the large linked part and the average briefest route, which use a mix of structural measures like average level, average briefest routes, centrality between, grouping factor, and alternatives to gauge the durability degree of a metro area's mobility setup in a severe climatic event. Gonçalves and Ribeiro [31] and Haggag et al. [32] suggested a model for evaluating urban path networks' durability by using the large linked part as a sign of strength and centrality and as a sign of network productivity.

Descriptive and numerical methods emphasize the varied approaches available for evaluating mobility durability. While descriptive models stress technical and administrative-based gauges, numerical models depend on output-based gauges and network structure. The work mainly centers on numerical methods, which provide detailed understanding but often need broad information. Conversely, descriptive ways are simply usable and need less information.

2.2. Interruption Kinds and Their Importance to Mobility Durability

Different interruptions affect mobility setups. These interruptions can be grouped into various kinds based on their type. **Table 1** displays the varied groups of interruptions and samples of those interruptions. Some of these interruptions, like those from nature, severe climatic events, and health crises, can be sudden and hard to forecast.

Table 1. Kinds of interruptions.

Interruption Kind	Samples
Nature and Climate-Triggered	Floods, repeated cold and melt, tempests, severe warmth, whirlwinds, snow and frost, quakes, blazes, slides and snowfalls
Artificial and Human-Triggered	Usage spikes, changing supply needs, illegal/attack actions, extended structure usage, quick population shifts, collisions, ocean rise, increased community input, health crises
Administrative	Asset handling, funding uncertainty, setup over limit, old structures, outdated plan, asset limits, political dangers, ordering
Financial	Tech interruption, trade uncertainty, shifting market states, mobility and supply expenses, ecological shifts, declining natural system, trade conflicts, downturn and slump

Source: National Academies of Sciences, Engineering, and Medicine.

Climate-linked interruptions like floods, heat periods and intense tempests are happening more often, thus stressing the need to prepare for more durable structures [30]. These interruptions frequently cause physical harm, journey lags, unreachability, financial loss, harms and fatalities [31], and in numerous instances, shared transit passenger numbers are badly influenced [32]. These interruptions heighten the current susceptibilities of shared transit setups, particularly in city areas [33]. Studies from advanced areas point out varied durability tactics. For example, Jing [33] and Hattingh [34] spot measures like better structure plan and upkeep, tech progress, and better interaction setups. Likewise, some examined examples provide main insights and physical and administrative measures to lessen the influence of natural calamities on transit setups. But, these studies center on advanced areas with greater assets and administrative abilities than emerging nations [35,36].

On the other hand, the health crisis triggered unmatched interruptions to mobility setups, altering travel needs and functions due to limits [37,38]. Shared transit managers and bodies had to apply tactics to guarantee service continuation. These included a reduction in vehicles and regularity, plus alterations in service provision [39,40]. These actions were frequently responsive, revealing shortfalls in preparation [41]. The health crisis revealed the need for flexible management and administrative teamwork in boosting system-wide durability.

Both climate-triggered and crisis-triggered interruptions influence varied aspects of shared transit durability. Climate-triggered interruptions mostly affect structure durability, while crisis-triggered interruptions mostly affect the administrative side of durability. Bolstering the durability of shared transit setups is thus vital, needing teamwork between bodies and users in creating durability tactics [42,43].

In brief, from the work review, main shortfalls persist. First, most studies centered on natural, climate-triggered interruptions or crisis effects separately, often in specific areas, thus missing a combined, cross-interruption viewpoint. Second, most studies use a numerical method to gauge durability, with restricted focus on descriptive evaluations including technical and administrative aspects. Third, restricted studies compare reactions across advanced and emerging countries or explore the combination of administrative, user, and tech factors, thus restricting the versatility of durability tactics to varied contexts.

This review fills these shortfalls by using a comparative descriptive model to examine how varied areas, across advanced and emerging contexts, react to climate and crisis interruptions. By reviewing four examples, the piece seeks to spot insights, assess reactions, and add to an improved comprehension of shared transit durability. results.

3. Methodology

This review uses a descriptive method, employing a mix of record review, web news pieces, and free-access shared transit passenger information to explore the durability of shared transit setups during severe climatic events and the health crisis. The approach is detailed below.

3.1. Information Gathering

Three main kinds of information were gathered: scholarly articles and policy records, web news pieces, and free-access transit passenger datasets. These origins were chosen to catch the varied aspects of durability and to verify details across different types of information.

The records were obtained via scholarly databases like web search engines for academics, science publishers, the mobility studies group publication database, and government and global bodies' sites. These databases were selected for their topic relevance and availability. The web search engine was used for its broad scope of academic pieces across varied fields, thus catching reviewed articles on both crises and climate-linked interruptions. The science publisher was employed for its emphasis on mobility, ecological studies, and city preparation, thus showing articles centered on durability and mobility. The mobility studies group database was picked for its full set of mobility-linked examples, reports, and review pieces, especially in advanced contexts, thus giving useful insights into adjustment durability tactics. The combined use of these databases guaranteed a full evaluation of durability in shared transit setups across varied geographic areas, matching the review article's main goals.

The work search was done using terms like shared mobility, durability, environmental shift, severe climate, crisis, health outbreak, and adjustment. The starting search gave 200 pieces. Then, the records were reviewed to grasp the practical sides of shared transit durability, adjustment tactics, and policies, and 131 pieces were selected for more review. The pieces and reports were checked for relevance to shared transit durability, adjustment actions and tactics, and management reactions to climate- and crisis-triggered interruptions. The addition rules needed that the records directly tackle mobility-linked interruptions due to severe climatic events or the health crisis between 2019 and 2024 and give understandings into reactions and adjustment actions. The removal rules excluded origins that missed detailed understandings or generalizations without proof. Following these rules, a total of 95 records were included in the review.

The web news pieces were obtained from area and country news sites using web news search and media stores. Targeted terms included storm halts, environmental shift happenings, shared transit halts, and health crises. These pieces were reviewed to pull real-time stories of climate-triggered interruptions, their effects on the mobility field, and the varied reactions toward restoration. Pieces were picked if they gave specific details of the interruptions, including their influences on shared transit and groups, and instant reactions by officials. The addition of these media origins gave a local viewpoint and details not in the work.

Two free-access datasets were used for the pattern review of passenger information:

The initial dataset was from the North American Shared Mobility Group, which holds transit passenger information in North America for varied travel modes, including major rail lines, light rail lines, traveler rail lines, cart buses, and traveler buses. The review chose to use the information on traveler rail lines and traveler buses since this information gives understandings into the influence of the crisis on shared mobility, particularly in an advanced context.

The second dataset was obtained from the Global Economic Group data tool and included information on the total length journeyed by shared transit riders in Central America using varied modes. The information pulled was from 2019 to 2023, which aided in exploring the crisis's influences on shared transit in Central America, which is seen as a nation in emerging areas.

The choice of these two datasets sought to show both advanced and emerging contexts, thus providing comparative understanding. Limits include variations in meanings between origins, which were noted in the review. Context prejudice was lessened by cross-checking observations with work and media origins and by placing each dataset in its context.

Literature Search and Selection Approach

The literature review was conducted between January 2010 and March 2024 using Scopus, Web of Science, Google Scholar, and selected institutional databases (e.g., World Bank, APTA, UITP). Core search terms included combinations of *"extreme weather events," "climate change," "public transport," "urban transit resilience," "Covid-19 pandemic,"* and *"4R resilience framework."*

Studies were included if they (i) examined impacts of climate extremes or pandemics on public transport systems, (ii) reported operational, ridership, or governance outcomes, and (iii) provided empirical or documented case-based evidence. Opinion pieces without case grounding and studies unrelated to urban transit were excluded. This approach ensures transparency while remaining appropriate for a scoping-style review.

Ridership in this section is measured in terms of total passenger trips per year, aggregated at the metropolitan system level, based on publicly reported agency statistics. While this metric captures overall demand trends, it does not account for trip length or passenger-kilometers traveled. Differences in data reporting practices, service coverage, and urban form mean that cross-region comparisons are indicative rather than strictly comparable and should be interpreted as contextual contrasts rather than direct performance rankings.

3.2. Example Choice

This piece reviews four examples: Major Storm in Britain; the spring 2022 floods in coastal Southern Africa; and two crisis-linked examples regarding shared transit passenger patterns in Central America and North America. The major storm was one of the worst tempests that lately hit Britain, causing major track and path mobility halts. This example gives a viewpoint on durability from an advanced context. The coastal floods were among the most destructive floods in Southern Africa, broadly harming mobility structures. This example gives an understanding of durability from an emerging context. The crisis-linked examples in Central America and North America center on shared transit passenger numbers and add to comprehending how crisis-triggered need shocks were handled from emerging and advanced contexts.

Together, these four examples match closely with the review goals by permitting the review to compare administrative ability, structures, and management in both advanced (Britain and North America) and emerging (Central America and Southern Africa) contexts. Also, the mix of climate and crisis-linked interruptions aids a review of how varied shocks affect distinct aspects of durability. The goal is not to broaden observations but to spot patterns of durability tactics that may be adjusted or thought about in other contexts.

1. Major Storm (Britain) → Storm Babet (October 2023), primarily affecting eastern Scotland and northern England; focus on rail (ScotRail/Network Rail) and major roads (A90, etc.).
2. Coastal Floods (Southern Africa) → April 2022 KwaZulu-Natal floods, centered on the eThekwini (Durban) metropolitan area; focus on road infrastructure and limited public transport impacts.
3. Covid-19 (North America) → United States/Canada transit systems (heavy rail + bus), using APTA/TransitCenter-style aggregated ridership.
4. Covid-19 (Central America) → Mexico (focus on Mexico City Metro + bus/BRT systems), using World Bank/national statistics on passenger-km.

The examples were picked using the following rules:

1. Information availability: Access to free reports, media records, and functional information, enabling a strong descriptive review of effects, reactions, and durability tactics;
2. Comparability: Choice of examples that show both advanced and emerging contexts, permitting administrative and structural comparison;
3. Interruption happenings: Examples centered on recent interruptions from 2019 onward.

3.3. Information Review

The information review involved various methods to pull main understandings from the information origins. A pattern review method was used to group reports and scholarly pieces into themes of durability, adjustment tactics, and policy models. This method allowed for spotting repeating patterns and insights from past interruptions. Likewise, the news pieces were pattern-organized to spot tactics and obstacles faced by shared transit officials in reacting to interruptions. The themes were created from the information origins, and repeated review and cross-checking of the pieces were used for confirmation to guarantee consistency in explanation. While pattern and content review are idea-linked, content review was used to pull specific details and to group the particular tactics, effects, and obstacles included in the comparative model detailed in **Table 2**.

Table 2. Comparative review model.

Durability Idea	Descriptive Sign: Climate-Triggered Interruption	Descriptive Sign: Crisis-Triggered Interruption
Strength	Physical wholeness of transit structures, upkeep record	Physical structure versatility to lowered ability
Alternatives	Presence of other roads, options or transit modes that can work during interruption	Presence of other movement choices (i.e., small-mobility)
Ingenuity	Administrative ability: gathering of funds, crisis reactions, alerts, interaction, aid	Range of service redesigns and structure growth, gathering of funds
Speed	Time to remove and restore key transit connections, pace of reaction and choice-making	Time for service restoration (i.e., passenger restoration), pace of applying choices

Pattern review was applied to the study of the shared transit information to compare passenger numbers before, during, and after the crisis. The aim was to spot passenger patterns, thus pointing out the influence of the crisis on shared transit usage. The information was reviewed using basic statistics and was graphed over time to show highs, lows, and restoration roads. The seen patterns were connected to the administrative reactions spotted in the work origins.

An organized comparative review model was created based on the 4R durability model, including gauges adjusted from Kim et al. [44] and KITE Projects [45], and a state mobility body. As shown in **Table 2**, this review model was systematically used on the picked examples. In this study, the 4R dimensions are interpreted as follows: **Robustness** refers to the ability of transit infrastructure and operations to withstand disruptions; **Redundancy** denotes the availability of alternative routes, modes, or backup systems; **Resourcefulness** captures institutional capacity to mobilize resources, adapt operations, and coordinate stakeholders; and **Rapidity** reflects the speed at which services are restored following disruptions. Ratings of Strong, Average, or Poor reflect relative performance based on documented evidence across cases.

Each example was given a descriptive durability score as outlined in the clearly outlined rules below:

- Very strong durability: All needs fulfilled (i.e., strength, alternatives, ingenuity, speed, all fulfilled well);
- Strong durability: Suitable output, but enhancements could be done;
- Average durability: Less than the wanted output. Priority to some enhancements;
- Poor durability: Bad output. Major enhancements needed.

Robustness (climate):

- Strong: minimal physical damage + effective pre-event mitigation (barriers/pumps/alerts);
- Average: moderate damage but partial protection;
- Poor: widespread structural failure + poor upkeep.

While scoring durability can bring some opinions, the rules were outlined consistently, and each score is based on the recorded information. This model serves as a comparative view rather than an absolute gauge.

The combined use of these methods backs the review's aim of revealing context-tailored durability tactics and administrative reactions, adding to a better comprehension of how shared transit setups adjust when faced with climate-linked events and crisis-triggered interruptions. Non-peer-reviewed sources are used primarily to document disruption timelines, infrastructure damage, and immediate operational responses. To ensure reliability, only official agency statements, audited reports, or corroborated media accounts were considered. Core analytical claims are supported primarily by peer-reviewed literature; where this is not possible, interpretations are presented cautiously.

4. Results

This part shows the observations from examples, reviewing the effects of climate-triggered and crisis-triggered interruptions and discussing the durability shown in each example. The review includes the 4R model (strength, alternatives, ingenuity, and speed) to strictly assess the actions applied, evaluate their success, and compare effects across varied contexts. The repeating patterns in interruptions, administrative reactions, and insights gained were reviewed and outlined.

4.1. Durability Evaluation

Using the descriptive review model created, the examples can be comparatively reviewed, catching the administrative and structural aspects of durability across varied contexts (see **Table 3**). Each example's seen actions and results were reviewed and grouped below.

The next parts provide a more detailed review of the durability shown in each example, drawing on the 4R model and expanding on the details provided in **Table 3**. The repeating patterns, like interruptions, administrative reactions, and insights gained, were reviewed and outlined in **Table 4**.

Table 3. Comparative review model for evaluating durability.

Example	Strength	Alternatives	Ingenuity	Speed	Rating
Major Storm (Britain)	Harm to roads and rail lines in some spots showed some susceptibility to floods; Crisis readiness	Track service halt shows a lack of alternatives in that mode; Some other roads were present	Strong ingenuity in gathering emergency options, funds for fixes and releasing alerts; Funding for long-term durability shows strong ingenuity	Speed in releasing alerts and reacting to interruptions right away; Restoration of mobility structures varied	Strong Durability

Table 3. *Cont.*

Example	Strength	Alternatives	Ingenuity	Speed	Rating
Coastal Floods (Southern Africa)	Structures are highly susceptible to floods; Bad upkeep of the drainage structures added to a lack of strength	Restricted alternatives, as some groups became unreachable	Ingenuity in providing aid; Ingenuity at the group level; Restricted ability to do quick harm and fixes	Slow starting reaction, evaluation of harm and restoration; Long-term plans for environmental shift adjustment show a focus on speed	Poor Durability
Covid-19 (North America)	Passenger drop shows susceptibility, but the setup can keep some service	Service growth and small-mobility combination guaranteed alternatives	Ingenuity in applying tactics to boost passenger numbers	Quick reaction in applying tactics; Gradual passenger restoration	Strong Durability
Covid-19 (Central America)	Passenger drop shows some susceptibility, but the setup can keep service	Path growth and quick bus transit (BRT) growth boosted alternatives	Ingenuity in providing funding, aids and tax relief, as well as structure growth	Quick restoration of bus passenger numbers, but rail lines are slowly restoring	Average Durability

Table 4. Comparative outline of observations.

Patterns	Major Storm (Britain)	Coastal Floods (Southern Africa)	Health Crisis (North America)	Health Crisis (Central America)
Interruption Type	Intense tempests and floods	Strong overflowing	Community health emergency	Community health emergency
Key impact	Mobility lags, track service shuts, and structure harm	Structure harm (main roads and connections) and groups unreachable	Sharp fall in shared transit usage	Passenger fall
Main interventions	Alerts, crisis fixes, and durability funding	Safe places, aid aid, and slow crisis fixes	Small-mobility, fare change, service redesign	Quick bus build, aids, and tax relief
4R Dimension Strengthened	Timely alert and partial fixes were sufficient, as track service was restored	Restoration was slow, thus showing restricted administrative ability	Average passenger restoration as restoration actions were applied quickly	Successful in the bus field as passenger numbers restored, not so much in rail lines
Evidence/Source	Value of overflow preparation, forward action and funding	Need for structure upkeep and quick administrative action	Worth of new ideas and quick administrative action	Worth of new ideas, funding and mode specific mobility preparation

4.2. Climate-Triggered Interruptions

4.2.1. Example of Major Storm in Britain

In autumn 2023, a severe storm hit Britain, causing major halts, including energy cuts, overflowing homes and roads, and journey lags due to path closures. Track options and water travels were halted, and a regional airport was briefly shut on a specific date [44]. The fix expense in a northern area alone was guessed at a certain amount [45,46]. **Figure 1** shows some of the harms to the mobility structures.

(**a**)

(**b**)

Figure 1. Harm to train lines. Origins: (**a**) Track Body in Garcia (2023); (**b**) "Overflow-hit dwellers 'won't be home for holiday'" (2023).

The starting reaction to the storm showed a level of strength in the form of crisis readiness. The release of early climate alerts and the use of barriers and pumps by the ecological body displayed a forward-thinking method to lessen the immediate effects. The alert setups were successful in protecting community safety and aiding moves and the barriers and pumps guarded many properties. The presence of such assets, plus an overflow durability plan for affected property holders, showed a degree of ingenuity in reacting to the emergency.

The speed of restoration varied across travel modes. Track service givers worked hard to clear waste and fix harm to restart service as fast as possible. Temporary fixes were done to some affected roads, allowing for the restart of traffic, though some badly damaged roads stayed shut [47,48], hence suggesting a need for betterment in handling key structural failures.

Regarding long-term restoration and adjustment, structural funding for drainage tasks, cold readiness plans, overflow risk reduction, and combined transit plans has been applied in different areas. These efforts center on boosting strength and improving the structure's ability to endure future interruptions. Also, the national body awarded funding for projects that center on growing durable structures. To guarantee durability in track options, the track body, which manages track options in the nation, planned to fund upkeep and update of ground works and drainage, smart structures, which includes distant watching and sensing, and review and new solutions [49]. These long-term funds further show a dedication to building long-term strength and alternatives into the mobility setup and back the "Strong Durability" rating in **Table 3**.

4.2.2. Example of the Coastal Spring 2022 Floods

In spring 2022, heavy rain in the coastal area, including a major city and the southern coast, resulted in bad overflowing that led to deaths, property damage, and destruction of structures, such as roads, connections, energy lines, and tubes [50,51]. **Figure 2** shows some of the harm to the path structures. Bad upkeep of the drainage structures and insufficient control of unofficial areas worsened the overflow effects [52]. The fixed expense was guessed to be around a certain amount [53]. The harm to roads and connections resulted in the mobility structures leaving many groups unreachable by roads [54,55].

Figure 2. Harm to roads due to spring 2022 floods in the coastal area.

Source: Local Reporter (2022).

The instant reaction to the overflow included the creation of safe places, the provision of aid to the affected families, and an emergency aid fund [56]. However, harm evaluation and fixes were lagged due to a lack of ability [57,58], thus blocking quick restoration. This lack of ability resulted in some dwellers fixing the damaged roads and connections to restore accessibility [59], showing a degree of group ingenuity in the face of administrative lagged action.

Traffic on some damaged roads was handled through detours or reopened after risk reviews and temporary fixes, with permanent fixes planned for later in 2022; however, the overall restoration process was slow. The presence of detour roads for traffic shift shows a level of alternatives, but this is restricted since some groups were left unreachable. Long-term adjustment efforts included boosting environmental shift awareness, improving access to early climate alerts, and encouraging local bodies to create environmental shift reaction plans, thereby boosting the area's adaptive ability and readiness. Overall, the example shows poor durability due to structural susceptibility, making it prone to the effects of the interruption and administrative ability limits, which led to lagged reaction and restoration.

4.3. Crisis-Triggered Interruptions

4.3.1. Example of Shared Transit Passenger in North America

Figure 3 shows the traveler track and bus passenger patterns in North America from 2014 to 2023. As shown, passenger numbers dropped sharply during 2020 due to the health crisis, with a gradual restoration afterward, though passenger levels remain lower than before the crisis. The drop in passenger numbers led to financial losses and a reduction in service levels. This drop shows an initial lack of strength in the face of the crisis.

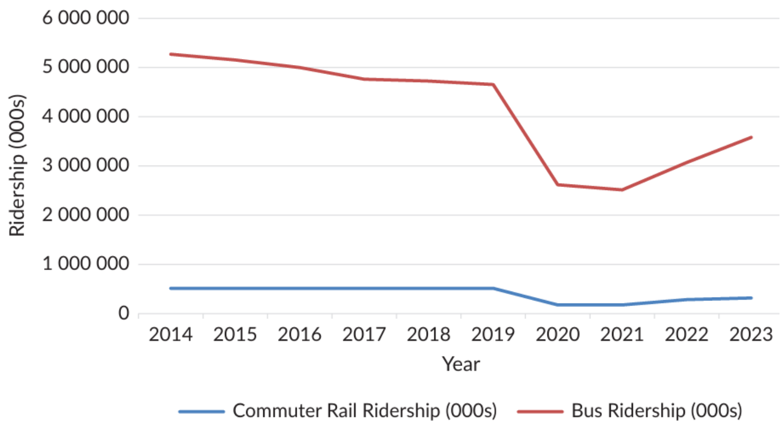

Figure 3. Annual unlinked passenger boardings (trips) for heavy rail and bus modes, aggregated across major U.S./Canadian systems.
Source: American Public Transportation Association (APTA) Ridership Reports, 2014–2023.

However, some service givers applied tactics to boost passenger numbers amid the crisis, which proved successful. These tactics included service growths, new track stops and bus options connecting to the track stops, bus path growth and redesign, transit sign priority and bus lanes, exclusive bus-only roads, small-mobility options, funding for new tech like wireless on buses and ticket machines, discounts for bike-sharing riders and quick bus features like jump queues and improved stops, free fare areas, and many other actions [60,61]. These measures represent a major adjustment to service provision in reaction to the interruption, showing ingenuity in spotting and applying solutions. The quick combination of small-mobility options and extending functions boosts alternatives.

Using such chances and making the best practices from the crisis period standard will guarantee the durability of shared transit in the post-crisis period alongside ensuring social fairness. The free-fare tactic has been one of the actions adjusted for after-crisis application, with the releasing guides to back state mobility bodies and transit groups in using these tactics. While passenger numbers are restoring, they are still below pre-crisis levels, showing that full restoration is ongoing and that quick return to pre-crisis levels is variable. The prompt doing of restoration plans and quick versatility show strong durability.

4.3.2. Example of Shared Transit Passenger in Central America

Figure 4 shows the yearly rider distances by bus in Central America from 2019 to 2023, showing a major drop in 2020 due to the crisis, followed by a strong, quick restoration in the following years, suggesting a high durability in this mode of travel. In a major city, small buses, which form a core part of the shared mobility setup, expanded their roads during the crisis to provide options to edge areas [62], showing ingenuity and boosting alternatives within the setup.

The track rider distances, as shown in **Figure 5**, decreased during the crisis and had a slow restoration thereafter, compared to the bus field. This points out different levels of durability within different modes of travel.

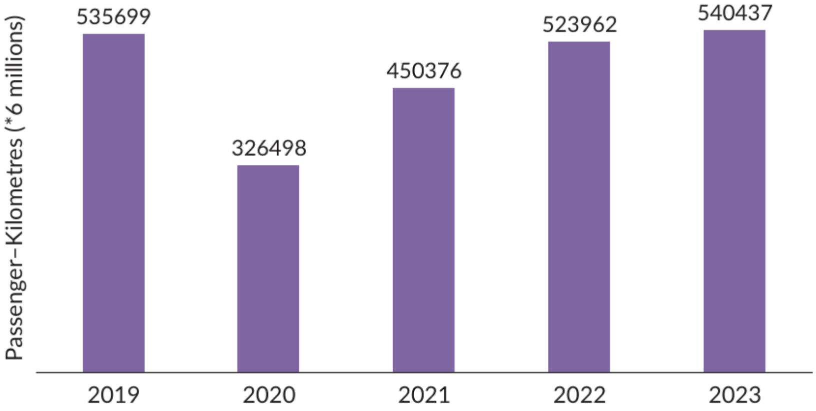

Figure 4. Passenger-kilometers traveled by bus.

Source: World Bank/national statistics, 2019–2023.

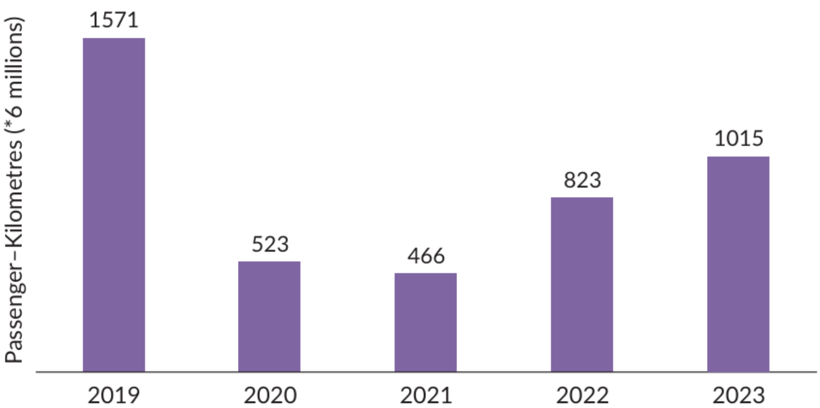

Figure 5. Passenger-kilometers traveled by metro.

Source: World Bank/national statistics, 2019–2023.

To foster restoration, energy aids and local tax reliefs were given for some time to back the shared transit options. Also, new quick bus structures were built, changing a car-centered corridor in a city into a dedicated quick bus path [63,64], thus improving alternatives. The government has also approved funding to boost rider and cargo track options [65–67]. These funds represent ingenuity and aim to improve the setup's alternatives and strength. While the reaction was generally prompt, the variation in mode restoration points out the need for betterment in administrative alignment to boost overall durability, hence the average durability rating [68–70].

4.4. Review

The examples reveal differences and likenesses in how shared transit setups react to climate- and crisis-triggered interruptions [71,72]. Both kinds of interruptions led to major reductions in transit service usage, though the interruption type varied. Climate events caused physical harm to structures, while the crisis mainly affected needs. This difference reflects the distinction between soft (habit, administrative, and policy-based) and hard (structure-based) parts of the transit setup [73,74]. The reactions to climate events centered on giving calamity aid, structure fix, and long-term adjustment actions, whereas the crisis reactions involved service changes and money back to service managers [75,76].

Regarding cross-example review of climate-triggered interruptions, Britain and coastal areas showed different obstacles and reactions. Britain's experience with the major storm showed the value of strength through alert setups and structure funds, as well as speed in reaction, as outlined in **Table 4**, which is consistent with alert setups coupled with funding in structures would boost durability [77–79].

In contrast, the coastal floods exposed susceptibilities related to structure upkeep and speed in emergency reaction and structure fixes. These observations align with a prior review, which pointed out the lack of consideration of climate change in the mobility field in the coastal city area, thus making it susceptible to climate-linked effects. The influence of socio-financial susceptibility and management shortfall in emerging areas, which block durability [80–82]. Both examples point out the need for long-term adjustment. Still, the coastal example shows the value of handling underlying socio-financial factors to improve the overall durability of the transit setup [83,84].

Comparing the North America and Central America examples, we see that both nations experienced a sharp fall in shared transit use. However, the speed of restoration differed. Central America's bus setup was restored quickly compared to North America. This could be due to socio-financial differences, policy reactions, and the structural features of the setup, as there was a center on small bus path growth and the building of a quick bus path, which backs alternatives [85,86]. Likewise, North America centered on service growth, path growth, small-mobility options, and tech progress. While direct numerical comparison is restricted, the review reveals understandings of factors affecting durability [87,88].

The comparative review pointed out the influence of interruption kind on durability output and the varying adjustment abilities of different country contexts. An outline of the implications of each climate-triggered interruption tends to expose the physical susceptibilities of transit structures and challenge administrative ability for quick reaction. In contrast, crisis-triggered interruptions stress functional versatility, new ideas, and policy adjustment. Ultimately, the 4R model reveals that durability depends not only on strong structures but also on management setups, readiness tactics, and new ideas [89–91].

4.5. Outline of Main Insights

- Value of Alert Setups: Alert setups are critical in lessening the influence of interruptions. Britain's successful release of emergency alerts and timely use of barriers successfully protected lives and structures. In contrast, Southern Africa's lack of such setups and lagged reaction points out the need for administrative models to apply early action plans.
- Asset Ability: Suitable money and human assets are necessary to guarantee timely reaction and restoration of transportation setups and structures. Southern Africa faced obstacles in doing an early risk review due to restricted ability, resulting in restoration lags, thereby forcing group-led restorative efforts. On the other hand, Britain, North America, and Central America could quickly react and adjust due to well-established bodies.
- Long-Term Funds in Durable Structures: Funding in durable structures is a priority. Britain centered on boosting the drainage structures, reducing overflow risk, and building smart structures. Likewise, North America and Central America funded new methods such as redesigning transit roads and growing quick bus structures. Despite asset limits, Southern Africa also aimed to handle structural vulnerabilities.
- Adjustment Through New Ideas: New methods used by North America, including the free-fare tactic, redesign of bus roads, small-mobility options and tech improvements, and Britain's funding in distant watching and sensing, show the potential for new ideas to back restoration and durability in shared transit setups.

Ridership refers to unlinked passenger boardings, unless otherwise stated. Because case reports demand using different metrics and temporal resolutions, cross-case comparisons are interpreted as qualitative contrasts in recovery processes and system capability, not direct performance rankings.

5. Conclusions

Growing durability in shared transportation setups is vital to handling the growing dangers posed by climate-triggered interruptions and worldwide health emergencies. This review points out the value of forward preparation, structure funding, and versatile tactics to lessen the effects of such obstacles. Examples from advanced and emerging countries show that durability needs a multi-sided method, covering physical structure betterments, administrative readiness, and user-centered actions. Main observations stress the need for funding for connected transit structures that can endure and adjust to shocks, including varied networks and service growth. Moreover, administrative ability bolstering is necessary through strong alert setups, using new solutions like distant sensing, digitization, and cross-body teamwork. Also, there is a need to order the upkeep of current structures to lessen susceptibility.

This review underscores the necessity of a full and inclusive method to durability, offering doable tactics to bolster shared transportation setups. However, transit setups are affected by community, political, and space setups. Therefore, the observations of this review should be explained with care, as the examples shown reflect varied contexts. Rather than offering worldwide solutions, the observations of this review offer understandings into durability-growing that can inform context-tailored tactics. The limits of this review include the reliance on secondary information, which might miss unrecorded durability actions. Moreover, the descriptive evaluation model used is opinion-based and depends on the availability and consistency of the information. Also, using the example method limits the broadening of the review's observations. It brings a certain level of prejudice, which may fail to fully cover the topic of shared transit durability across varied areas.

Future studies should center on doing more local examples based on primary information to catch the actual experiences of the interruptions, growing a standard durability gauge that can be used across varied contexts while guaranteeing local relevance and checking the durability of unofficial shared transit setups to these interruptions, especially in emerging areas, which are rarely reported. Ultimately, this review offers understanding into the durability of shared transit setups, stressing the need for inclusive, context-tailored methods. Adjusting the insights from this review will be vital in enabling the versatility and restoration of shared transit setups in the event of an interruption.

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References

[1] Srikanth, S., Kanimozhee, S., Ramireddy, S., 2023. Modelling of pre and post COVID-19 impact on employee's mode choice behavior. Innovative Infrastructure Solutions. 8(1), 11. DOI: https://doi.org/10.1007/s41062-022-00990-x

[2] National Academies of Sciences, Engineering, and Medicine, 2017. Improving the Resilience of Transit Systems Threatened by Natural Disasters, Volume 3: Literature Review and Case Studies. The National Academies Press: Washington, DC, USA.

[3] American Public Transportation Association, n.d. Ridership Data Archives. Available from: https://www.apta.com/news-research/public-transit-statistics/ridership-data/archives/ (cited 13 May 2025).

[4] American Public Transportation Association, 2021. On the horizon: Planning for post-pandemic travel. Available from: https://www.apta.com/review-technical-resources/review-reports/on-the-horizon-planning-for-post-pandemic-travel (cited 10 June 2025).

[5] Angell, C., Potoglou, D., 2022. An insight into the impacts of COVID-19 on work-related travel behaviours in the Cardiff Capital Region and following the UK's first national lockdown. Cities. 124, 103602. DOI: https://doi.org/10.1016/j.cities.2022.103602

[6] Arana, P., Cabezudo, S., Peñalba, M., 2014. Influence of weather conditions on transit ridership: A statistical study using data from smartcards. Transportation Research Part A: Policy and Practice. 59, 1–12. DOI: https://doi.org/10.1016/j.tra.2013.10.019

[7] Pan, S., Yan, H., He, J., et al., 2021. Vulnerability and resilience of transportation systems: A recent literature review. Physica A: Statistical Mechanics and Its Applications. 581, 126235. DOI: https://doi.org/10.1016/j.physa.2021.126235

[8] Aydin, N.Y., Duzgun, H.S., Wenzel, F., et al., 2018. Integration of stress testing with graph theory to assess the resilience of urban road networks under seismic hazards. Natural Hazards. 91, 37–68. DOI: https://doi.org/10.1007/s11069-017-3112-z

[9] Beldarrain, G.G., Carvajal Ortega, C.A., Baan, A., et al., 2022. Framing resilience in public transportation systems, inspired by biomimicry. In Proceedings of the Design Research Society 2022 (DRS2022), Bilbao, Spain, 25 June–3 July 2022. DOI: https://doi.org/10.21606/drs.2022.323

[10] Bo, K., Teng, J., Zhang, C., et al., 2021. Commuting in the storm: Adaptation of transit riders and measures for transit operator—A case in Shanghai. Journal of Advanced Transportation. 2021(1), 6622461. DOI: https://doi.org/10.1155/2021/6622461

[11] Böcker, L., Uteng, T.P., Liu, C., et al., 2019. Weather and daily mobility in international perspective: A cross-comparison of Dutch, Norwegian and Swedish city regions. Transportation Research Part D: Transport and Environment. 77, 491–505. DOI: https://doi.org/10.1016/j.trd.2019.07.012

[12] Briginshaw, S., 2024. Mexican president confirms passenger rail revival. Available from: https://www.railjournal.com/passenger/main-line/mexican-president-confirms-passenger-rail-revival (cited 21 May 2025).

[13] Bruneau, M., Chang, S.E., Eguchi, R.T., et al., 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra. 19(4), 733–752. DOI: https://doi.org/10.1193/1.1623497

[14] Burchart-Korol, D., Folęga, P., 2019. Impact of road transport means on climate change and human health in Poland. Promet – Traffic & Transportation. 31(2), 195–204. DOI: https://doi.org/10.7307/ptt.v31i2.3074

[15] Buthelezi, L., 2022. After record KZN flood claims, Santam is working with municipalities to prevent future disasters. Available from: https://www.news24.com/business/companies/after-record-kzn-flood-claims-santam-is-working-with-municipalities-to-prevent-future-disasters-20220902 (cited 23 August 2025).

[16] Calder, S., 2023. Storm Babet travel advice: How the extreme weather is affecting trains, flights and ferry services. Available from: https://www.independent.co.uk/travel/news-and-advice/storm-babet-trains-travel-roads-latest-b2432395.html (cited 11 July 2025).

[17] Calnek-Sugin, T., Heeckt, C., 2020. Mobility for the masses: The essential role of informal transport in the COVID-19 recovery. Available from: https://www.lse.ac.uk/cities/publications/blogs/mobility-for-the-masses (cited 1 June 2025).

[18] Enoch, B., 2022. Durban residents repair flood damage, give up on government. Available from: https://groundup.org.za/article/durban-residents-repair-flood-damage-give-up-on-government (cited 4 July 2025).

[19] Chen, R., Shalaby, A., Silva, D.D., 2024. Trends in Toronto's subway ridership recovery: An exploratory analysis of Wi-Fi records. Transportation Research Record. 2678(11), 1156–1176. DOI: https://doi.org/10.1177/03611981241242775

[20] Colorado Department of Transportation, n.d. 4R Framework for Identifying and Evaluating Resiliency in Transportation System Assets and Organizations. Available from: https://www.codot.gov/programs/

planning/assets/risk-and-resiliency/4r-framework-remediated.pdf (cited 17 July 2025).

[21] Kwazulu-Natal Province, 2023. Reflecting on the April/May 2022 KZN floods: One year later. Available from: https://www.kznedtea.gov.za/documents/Floods%20Article-Modified.pdf (cited 11 August 2025).

[22] Department of Planning, Monitoring and Evaluation, 2023. Rapid Assessment of the Government's Intervention on the April 2022 Flood Disaster in KwaZulu-Natal, Eastern Cape and North West. Department of Planning, Monitoring and Evaluation: Pretoria, South Africa. Available from: https://www.dpme.gov.za/keyfocusareas/evaluationsSite/Evaluation%20Reports/2.4%20Final%20Report%20on%20Rapid%20Assessment%20of%20Flood%20Disaster%20Interventions.pdf

[23] Suffolk County Council, 2023. An update following Storm Babet. Available from: https://sweffling-pc.gov.uk/assets/Sweffling-Parish-Council/East-Suffolk-D-C-Reports/Storm-Babet-briefing-Framlingham-FINAL-1.pdf (cited 7 July 2025).

[24] English, E., 2023. Seven roads in East Cork damaged by Storm Babet blocked by padlocked gates. Available from: https://www.irishexaminer.com/news/munster/arid-41294434.html (cited 18 July 2025).

[25] Chan, R., Schofer, J.L., 2015. Measuring transportation system resilience: Response of rail transit to weather disruptions. Natural Hazards Review. 17(1), 05015004. DOI: https://doi.org/10.1061/(ASCE)NH.1527-6996.0000200

[26] Environment Agency, 2023. Nearly 100,000 properties protected from flooding during Storm Babet, but threat remains. Available from: https://www.gov.uk/government/news/rolling-news-story-flooding-from-storm-babet (cited 22 June 2025).

[27] Federal Transit Administration, 2024. Effects of the COVID-19 pandemic on transit ridership and accessibility. Federal Transit Administration: Washington, DC, USA. Available from: https://www.transit.dot.gov/sites/fta.dot.gov/files/2024-08/FTA-Report-0268-Effects-of-the-COVID-19-Pandemic-on-Transit-Ridership-and-Accessibility.pdf

[28] BBC, 2023. Flood-hit residents 'won't be home for Christmas'. Available from: https://www.bbc.com/news/uk-scotland-67186878 (cited 23 July 2025).

[29] Fraser, A.M., Chester, M.V., 2017. Transit planning and climate change: Reducing rider's vulnerability to heat. In Proceedings of the International Conference on Sustainable Infrastructure 2017, New York, NY, USA, 26–28 October 2017; pp. 456–464. DOI: https://doi.org/10.1061/9780784481202.043

[30] Freckleton, D., Heaslip, K., Louisell, W., et al., 2012. Evaluation of resiliency of transportation networks after disasters. Transportation Research Record. 2284(1), 109–116. DOI: https://doi.org/10.3141/2284-13

[31] Gonçalves, L., Ribeiro, P., 2020. Resilience of urban transportation systems. Concept, characteristics, and methods. Journal of Transport Geography. 85, 102727. DOI: https://doi.org/10.1016/j.jtrangeo.2020.102727

[32] Haggag, M., Siam, A.S., El-Dakhakhni, W., et al., 2021. A deep learning model for predicting climate-induced disasters. Natural Hazards. 107, 1009–1034. DOI: https://doi.org/10.1007/s11069-021-04620-0

[33] Jing, J., 2021. Post-Sandy flood resiliency in NYC: How to prevent subway systems from increasing storm surges. Brown University: Providence, RI, USA.

[34] Hattingh, M., 2022. What did cause the April KZN floods? Water Wheel. 21(4), 24–27.

[35] Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics. 4, 1–23. DOI: https://doi.org/10.1146/annurev.es.04.110173.000245

[36] Hughes, J.F., Healy, K., 2014. Measuring the Resilience of Transport Infrastructure. NZ Transport Agency: Wellington, New Zealand.

[37] Imran, M., Cheyne, C., Harold, H., 2014. Measuring Transport Resilience: A Manawatu-Wanganui Region Case Study. Resource and Environmental Planning, Massey University: Palmerston North, New Zealand. Available from: https://mro.massey.ac.nz/items/7f0e3154-cd67-41c1-b879-bdd3790dc561

[38] Internet Geography, 2023. Storm Babet case study. Available from: https://www.internetgeography.net/storm-babet-case-study (cited 11 July 2025).

[39] Jenelius, E., Cats, O., 2015. The value of new public transport links for network robustness and redundancy. Transportmetrica A: Transport Science. 11(9), 819–835. DOI: https://doi.org/10.1080/23249935.2015.1087232

[40] Ji, T., Yao, Y., Dou, Y., et al., 2022. The impact of climate change on urban transportation resilience to compound extreme events. Sustainability. 14(7), 3880. DOI: https://doi.org/10.3390/su14073880

[41] Haines, A., 2020. Resilience of Rail Infrastructure: Interim Report to the Secretary of State for Transport Following the Derailment at Carmont, Near Stonehaven. Available from: https://assets.publishing.service.gov.uk/media/5f9162add3bf7f35ecfe89e1/resilience-of-rail-infrastructure-interim-report.pdf (cited

23 July 2025).
[42] Kafalenos, R.S., Leonard, K.J., Beagan, D., et al., 2008. What are the implications of climate change and variability for Gulf Coast transportation? In: Savonis, M.J., Burkett, V.R., Potter, J.R. (Eds.). Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. U.S. Climate Change Science Program: Washington, DC, USA. pp. 1–63.
[43] Kermanshachi, S., Li, J., Jahan Nipa, T., 2021. Development of a multi-level dynamic model to measure the resilience level of transportation infrastructure networks. Transportation Consortium of South-Central States: Baton Rouge, LA, USA. Available from: https://repository.lsu.edu/transet_pubs/133
[44] Kim, K., Francis, O., Yamashita, E., 2018. Learning to build resilience into transportation systems. Transportation Research Record. 2672(1), 30–42. DOI: https://doi.org/10.1177/0361198118786622
[45] KITE Projects, 2023. Back on track: How Network Rail restored the railway after storms Babet & Ciarán tore through the UK. Available from: https://www.kite-projects.co.uk/post/back-on-track-how-network-rail-restored-the-railway-after-storms-babet-ciarán-tore-through-the-uk
[46] Lee, S., Kim, J., Cho, K., 2024. Temporal dynamics of public transportation ridership in Seoul before, during, and after COVID-19 from urban resilience perspective. Scientific Reports. 14(1), 8981. DOI: https://doi.org/10.1038/s41598-024-59323-w
[47] Leobons, C.M., Gouvêa Campos, V.B., de Mello Bandeira, R.A., 2019. Assessing urban transportation systems resilience: A proposal of indicators. Transportation Research Procedia. 37, 322–329. DOI: https://doi.org/10.1016/j.trpro.2018.12.199
[48] de Souza Lima, G.C.L., de Carvalho, G.S.D., Figueiredo, M.Z., 2020. Incomplete contracts for bus service during the COVID-19 pandemic. Revista de Administração Pública. 54, 994–1009. DOI: https://doi.org/10.1590/0034-761220200292 (in Portuguese)
[49] Los Angeles County Metropolitan Transit Authority, 2015. Resiliency Indicator Framework. Los Los Angeles County Metropolitan Transit Authority: Los Angeles, CA, USA. Available from: http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf
[50] Magubane, T., 2023. eThekwini highlights repair, rebuilding work done one year after April floods. Available from: https://www.iol.co.za/mercury/news/ethekwini-highlights-repair-rebuilding-work-done-one-year-after-april-floods-14a6915f-78eb-443e-89ef-37d033e00e9f (cited 11 July 2025).
[51] National Academies of Sciences, Engineering, and Medicine, 2024. Incorporating Resilience into Transportation Networks. The National Academies Press: Washington, DC, USA. DOI: https://doi.org/10.17226/27919
[52] Mepparambath, R.M., Huynh, H.N., Oon, J., et al., 2023. The impact of COVID-19 pandemic on the fundamental urban mobility theories using transit data from Singapore. Transportation Research Interdisciplinary Perspectives. 21, 100883. DOI: https://doi.org/10.1016/j.trip.2023.100883
[53] Monama, T., 2022. Flood costs revised from R950 billion to R17 billion—but KZN government says was 'honest error.' Available from: https://www.news24.com/news24/southafrica/news/flood-costs-revised-from-r950-billion-to-r17-billion-but-kzn-government-says-was-honest-error-20220425 (cited 11 July 2025).
[54] Stefani, F., 2023. Storm Babet prompts closure of train lines across the Highlands tomorrow and Friday. Available from: https://www.johnogroat-journal.co.uk/news/storm-babet-prompts-closure-of-train-lines-across-the-highla-330013 (cited 11 June 2025).
[55] Murray-Tuite, P.M., 2006. A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. In Proceedings of the 2006 Winter Simulation Conference, Monterey, CA, USA, 3–6 December 2006; pp. 1398–1405. DOI: https://doi.org/10.1109/WSC.2006.323240
[56] Maluleke, T., 2022. First Special Report on Flood Relief Funds. Auditor-General South Africa: Pretoria, South Africa. Available from: https://www.agsareports.co.za/wp-content/uploads/2022/09/First-special-report-on-flood-relief-funds-2022-1.pdf
[57] National Academies of Sciences, Engineering, and Medicine, 2024. Sustaining Zero-Fare Public Transit in a Post COVID-19 World: A Guide for State DOTs. The National Academies Press: Washington, DC, USA.
[58] West Bridgford Wire, 2025. Nottinghamshire: Highways update shows record £66m investment and 25,000 pothole repairs in first half year. Available from: https://westbridgfordwire.com/nottinghamshire-highways-update-shows-25000-potholes-repairs-in-first-half-year (cited 17 July 2025).
[59] Omer, M., Mostashari, A., Lindemann, U., 2014. Resilience analysis of soft infrastructure systems. Procedia Computer Science. 28, 565–574. DOI: https://doi.org/10.1016/j.procs.2014.03.069
[60] Arkell, B.P., Darch, G.J.C., 2006. Impact of climate change on London's transport network. Proceedings of

the Institution of Civil Engineers – Municipal Engineer. 159(4), 231–237. DOI: https://doi.org/10.1680/muen.2006.159.4.231

[61] Pregnolato, M., Dawson, D.A., 2018. Adaptation investments for transport resilience: Trends and recommendations. International Journal of Safety and Security Engineering. 8(4), 515–527. DOI: https://doi.org/10.2495/SAFE-V8-N4-515-527

[62] Jain, A., Babu, A., 2025. Urban green spaces and their indispensable necessity in the context of cities experiencing rapid urbanization in India: An analysis of current trends and future implications. International Journal of Environmental Pollution and Environmental Modelling. 8(2), 122–134.

[63] Revi, A., Satterthwaite, D., Aragón-Durand, F., et al., 2014. Towards transformative adaptation in cities: The IPCC's Fifth Assessment. Environment & Urbanization. 26(1), 11–28. DOI: https://doi.org/10.1177/0956247814523539

[64] Rogers, D., Tsirkunov, V., 2010. Global Assessment Report on Disaster Risk Reduction: Costs and Benefits of Early Warning Systems. World Bank: Washington, DC, USA.

[65] Intergovernmental Panel on Climate Change (IPCC), 2023. Climate Change 2023 Synthesis Report. IPCC: Geneva, Switzerland. Available from: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

[66] Jain, A., Garg, C., 2025. Overcoming the barriers of sustainable urban development: An examination of urban morphology and transportation systems. Journal of Transportation Systems. 10(3), 1–12.

[67] Satterthwaite, D., Archer, D., Colenbrander, S., et al., 2020. Building resilience to climate change in informal settlements. One Earth. 2(2), 143–156. DOI: https://doi.org/10.1016/j.oneear.2020.02.002

[68] Serulle, N.U., 2011. Transportation network resiliency: A fuzzy systems approach. Utah State University: Logan, UT, USA.

[69] Shang, W.-L., Lv, Z., 2023. Low carbon technology for carbon neutrality in sustainable cities: A survey. Sustainable Cities and Society. 92, 104489. DOI: https://doi.org/10.1016/j.scs.2023.104489

[70] Acierto, J.M.L., Quilla, S.M.H., Valencia, B.J.N., et al., 2023. Comparative study on Urban Transport and the Environment (CUTE) framework as strategy for the reduction of carbon dioxide emissions of road vehicles at Zapote Street. Planning Malaysia. 21(28). DOI: https://doi.org/10.21837/pm.v21i28.1311

[71] Mudefi, E., 2023. Disaster management 'deeds' in the context of April 2022 KwaZulu-Natal floods: A scoping review. International Journal of Disaster Risk Reduction. 98, 104122. DOI: https://doi.org/10.1016/j.ijdrr.2023.104122

[72] Ivarsson, E., Stokenberga, A., Fulponi, J.I., 2023. The COVID-19 Mark on Urban Mobility: A Tale of Two Cities' Journey to Recovery. World Bank: Washington, DC, USA. DOI: https://doi.org/10.1596/1813-9450-10484

[73] Suffolk County Council, 2023. 4.7 million litres of water and 8,412 drains cleared since Storm Babet battered Suffolk one month ago. Available from: https://www.suffolk.gov.uk/council-and-democracy/council-news/4.7-million-litres-of-water-and-8412-drains-cleared-since-storm-babet-battered-suffolk-one-month-ago (cited 8 July 2025).

[74] Sun, W., Bocchini, P., Davison, B.D., 2020. Resilience metrics and measurement methods for transportation infrastructure: The state of the art. Sustainable and Resilient Infrastructure. 5(3), 168–199. DOI: https://doi.org/10.1080/23789689.2018.1448663

[75] Yates, T., 2023. Project Spotlight: Boosting UK infrastructure resilience against climate change. Available from: https://www.ukcric.com/outputs/project-spotlight-boosting-uk-infrastructure-resilience-against-climate-change/ (cited 21 July 2025).

[76] Tao, S., Corcoran, J., Rowe, F., et al., 2018. To travel or not to travel: 'Weather' is the question. Modelling the effect of local weather conditions on bus ridership. Transportation Research Part C: Emerging Technologies. 86, 147–167. DOI: https://doi.org/10.1016/j.trc.2017.11.005

[77] Testa, A.C., Furtado, M.N., Alipour, A., 2015. Resilience of coastal transportation networks faced with extreme climatic events. Transportation Research Record. 2532(1), 29–36. DOI: https://doi.org/10.3141/2532-04

[78] United States Environmental Protection Agency, 2025. Transportation, Air Pollution and Climate Change. Available from: https://www.epa.gov/transportation-air-pollution-and-climate-change (cited 11 July 2025).

[79] Thoithi, W., Blamey, R.C., Reason, C.J., 2022. April 2022 floods over East Coast South Africa: Interactions between a mesoscale convective system and a coastal meso-low. Atmosphere. 14(1), 78. DOI: https://doi.org/10.3390/atmos14010078

[80] Tierney, K., Bruneau, M., 2007. Conceptualizing and measuring resilience: A key to disaster loss reduction. Available from: https://onlinepubs.trb.org/onlinepubs/trnews/trnews250_p14-17.pdf (cited 11 July 2025).

[81] Tonn, G., Czajkowski, J., Kunreuther, H., et al.,

2020. Measuring transportation infrastructure resilience: Case study with Amtrak. Journal of Infrastructure Systems. 26(1), 05020001. DOI: https://doi.org/10.1061/(ASCE)IS.1943-555X.0000526

[82] Tori, S., de Séjournet, A., Macharis, C., 2023. Reactions of the public transport sector to the COVID-19 pandemic. Insights from Belgium. Travel Behaviour and Society. 31, 244–253. DOI: https://doi.org/10.1016/j.tbs.2023.01.001

[83] Tabassum, N., Kalantari, H.A., Kaniewska, J., et al., 2024. Ways of increasing transit ridership—lessons learned from successful transit agencies. Case Studies on Transport Policy. 19, 101362. DOI: https://doi.org/10.1016/j.cstp.2024.101362

[84] Ward, S., 2023. Roads reopen after Storm Babet as £32,000 raised to help Brechin. Available from: https://www.standard.co.uk/news/environment/roads-dundee-aberdeenshire-scotland-gofundme-b1115611.html (cited 21 July 2025).

[85] Zorgati, I., Zorgati, H., Zaabi, E., 2021. Public transportation and service quality management during the COVID-19 outbreak: A case study of Tunisia. Problems and Perspectives in Management. 19(3), 298–308. DOI: https://doi.org/10.21511/ppm.19(3).2021.24

[86] Welle, B., Kustar, A., Tun, T.H., et al., 2023. Post-pandemic, public transport needs to get back on track to meet global climate goals. Available from: https://thecityfix.com/blog/post-pandemic-public-transport-needs-to-get-back-on-track-to-meet-global-climate-goals (cited 22 July 2025).

[87] World Bank, 2024. Mexico Green & Resilient Transport: Urban Public Transport. World Bank: Washington, DC, USA. Available from: https://documents1.worldbank.org/curated/en/099062424183033037/pdf/P1772791af9eca0aa19fbd1948f0ead32a5.pdf (cited 7 July 2025).

[88] Wu, J., Liao, H., 2020. Weather, travel mode choice, and impacts on subway ridership in Beijing. Transportation Research Part A: Policy and Practice. 135, 264–279. DOI: https://doi.org/10.1016/j.tra.2020.03.020

[89] Xia, Y., Van Ommeren, J.N., Rietveld, P., et al., 2013. Railway infrastructure disturbances and train operator performance: The role of weather. Transportation Research Part D: Transport and Environment. 18, 97–102. DOI: https://doi.org/10.1016/j.trd.2012.09.008

[90] Zhou, Y., Wang, J., Yang, H., 2019. Resilience of transportation systems: Concepts and comprehensive review. IEEE Transactions on Intelligent Transportation Systems. 20(12), 4262–4276. DOI: https://doi.org/10.1109/TITS.2018.2883766

[91] Watt, E., 2024. Are seismometers valuable instrumentation for monitoring weather events? A Northeast and Central Scotland case study. The Elphinstone Review. 10(1), 88–117.