From Floods to Heatwaves: Strengthening Urban Transport amidst Changing Climate

Experiences from China on Climate-Proofing Urban Mobility Systems

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Content

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1. Introduction

Urban mobility systems worldwide face growing threats from extreme weather events (EWEs), including droughts, heatwaves, floods, and storm surges. These events often result in severe disruptions to transport infrastructure, endangering public safety and impeding economic activities in cities. Meanwhile, climate change continues to intensify both the frequency and intensity of EWEs, amplifying the urgency to enhance urban transport resilience[1].

Recent data underscores the severity of these challenges. Globally, the incidence of EWEs increased by 9 % between 2012–2016 and 2017–2021, with the number of incidents rising from 1,818 to 1,982, affecting millions of people worldwide[2]. On a regional level, the impact is particularly stark. In July 2024 alone, EWEs in China impacted 23 million individuals and led to direct economic losses estimated at USD 10 billion[3]. In Germany, the "Jahrhundertflut" (once in a century flood) in the Ahrtal region in 2021 caused 141 deaths, left more than 750 people severely injured, and incurred an estimated EUR 4.5 billion in direct damages to the transport sector, along with EUR 2.5 billion in indirect losses, making it the most damaging extreme weather event in German History[3]. The disaster also reached beyond Germany's borders, inflicting significant damage on neighbouring countries, including France, Belgium, and Austria. Taken together, these examples highlight the tremendous vulnerability of transport systems to climatic shocks and underscore the need for climate-adaptation measures explicitly tailored to urban contexts.

Transportation, particularly urban mobility, holds a unique position in the context of extreme weather events. It is both highly vulnerable to the destructive impacts of such events and poses significant risks during emergencies, such as when evacuation routes are compromised. Simultaneously, the transport sector remains one of the largest contributors to CO_2 emissions while being a crucial lever for a more sustainable, low-emission future. This pluralistic role of urban mobility – as both a contributor to and an affected party of climate change – requires resilient strategies for urban planners and policymakers. The interplay between urban mobility and climate change is depicted in figure 1. This brief paper gives an overview of the various effects of mobility damage in the context of EWEs for both policymakers, transport planners and a general audience in Germany, whilst offering insights into new case studies and adaptation approaches from China.

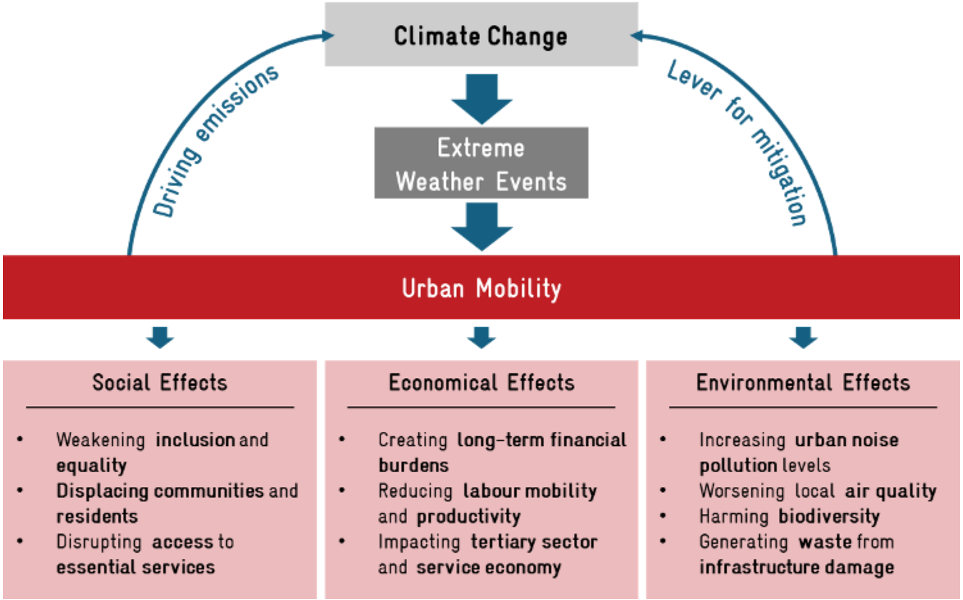

Figure 1: Interplay Urban Mobility, Extreme Weather Events and Climate Change

(I) Urban Mobility: Cause and Potential Lever

The broader transport sector, and urban mobility in particular, are highly vulnerable to extreme weather events. High-impact events such as floods and rainstorms frequently lead to road washouts, structural damage, and widespread disruptions to transport systems. A stark example occurred in Henan Province, China, in 2021, when severe flooding inundated rail tunnels, necessitating the rescue of 500 individuals and resulting in 12 fatalities. The flooding caused extensive damage to roads, forced the evacuation of 200,000 people, and led to widespread suspensions of flights and train services, paralysing mobility across the region[5].

At the same time, the transport sector remains a significant contributor to global greenhouse gas emissions. In China, transport accounted for approximately 10 % of the nation's total carbon emissions in 2020, with emissions rising dramatically from 372 million tonnes in 2005 to 983 million tonnes in 2020, a staggering 264 % increase[6]. Much of this growth can be attributed to urban mobility, driven by rapid urbanisation and a surge in private vehicle ownership[7]. Similarly, in Germany, the mobility sector emitted approximately 148 million tonnes of CO_2-equivalents in 2022, representing about 20 % of the country's total emissions[8]. At the same time, urban transport presents a significant opportunity for decarbonisation, offering substantial potential through the adoption of advanced technologies, such as hydrogen fuel cells and electric powertrains, as well as by encouraging a modal shift. Estimates suggest that by 2060, structural changes in China's urban transport systems – such as prioritising public buses over private cars and improving vehicle occupancy rates – could achieve the second-highest emissions reduction potential, cutting cumulative road transport emissions by 23 %. This emphasises the pivotal role of urban mobility in driving major progress toward decarbonisation and combating climate change[9].

(III) Social Impacts of Damages and Disruptions on Urban Mobility

In the context of urban mobility, the importance of resilience extends beyond immediate risk mitigation due to its far-reaching social, economic, and environmental implications. Urban mobility systems, particularly public transport, serve as critical lifelines, connecting communities to essential services such as food, education, healthcare, and employment[5, 10]. These networks form the backbone of equitable access to social infrastructure, helping ensure societal inclusion and equality. For instance, research conducted by BCG in Paris demonstrates how well-functioning public transport reduces barriers to opportunity for underserved communities by providing reliable access to employment and essential resources[11]. Disruptions to these networks, however, can have compounding effects, particularly in rapidly urbanising areas. With nearly 70 % of the global population projected to live in urban areas by 2040, the stakes for resilient mobility systems are only increasing[12]. When EWEs damage these systems, they amplify inequalities, hinder economic mobility, and prolong recovery periods, disproportionately affecting vulnerable populations. Additionally, being critical infrastructure, public transport plays a crucial role in emergency response and relief directly after disasters, further emphasising its need for resilience[13].

(III) Economic Impacts of Urban Mobility Damages and Disruptions

Additionally, urban infrastructure, by its nature, is not only heavy in CO_2 emissions during construction, but also requires significant investment with long amortisation periods, making forward-thinking towards resilient systems unavoidable. It is expensive and has limited room for adaptation, necessitating planning for future-proof solutions[14]. While direct economic losses due to infrastructure damage are already burdensome, it is projected that the indirect costs caused by extreme weather events will become overwhelmingly dominant over time. In China, in particular, the economic landscape is predicted to change, with the tertiary (service) sector, including industries like real estate, finance, and wholesale/retail trade, becoming increasingly important to economic development. However, these sectors are also most vulnerable to climatic economic losses. Studies predict that, under a "business as usual" scenario, by 2100, 97.96 % of the total economic losses are estimated to come from cascading indirect effects on these sectors, not the initial direct damage. Simultaneously, the average annual increase in climatic economic losses is estimated to be up to 8.5 %, mainly caused by the destruction of critical transport infrastructure and its cascading effects, leading to a grim perspective on the economic consequences caused by climate change-accelerated extreme weather events in the future[10].

(IV) Environmental Impacts of Urban Mobility Damages and Disruptions

While the nature of urban mobility as both a cause and a lever for mitigating climate change is often discussed, its more immediate effects on urban environmental health are equally pressing. For example, in China, air quality in its megacities has long been a health concern with public e-mobility infrastructure playing a pivotal role in addressing these issues by reducing local emissions from transport[15]. The electrification of public bus fleets has already shown promising results in cities like Shenzhen, which fully electrified its public bus system in 2017 and its taxi fleet by 2019. This transition resulted in noticeable improvements in air quality and reductions in noise pollution, underscoring the broader health and environmental benefits of sustainable urban mobility systems[16].

To make urban mobility systems "future-proof" by enhancing their resilience, the concept of adaptive capacity is essential. It refers to the ability of transport planning and governance systems to minimise disruptions over the lifecycle of transport infrastructure while capitalising on opportunities presented by a changing climate. To do so, it is essential to robust design, financial resources, and operational capabilities, enabling them to withstand and recover from climate-induced risks. While being thousands of kilometers apart, China and Germany share not only the common goal of finding strategies for sustainable urban transport, they also face a similar increasing threat imposed by EWEs to reach that goal. In this context, this paper highlights different strategies and frameworks aiming to enhance the resilience of urban mobility systems, ensuring their capacity to adapt to the growing challenges of a changing climate while continuing to serve as a backbone for sustainable urban development.

2. Effects of Climate Change on Urban Mobility Infrastructure

Urban areas possess distinct climatic characteristics, including higher surface and air temperatures, reduced wind speeds, and lower air quality compared to their natural surroundings. These urban climate effects, already significant, are further exacerbated by global climate change. As temperatures continue to rise, urban areas are expected to face worsening thermal conditions and declining air quality, disproportionately impacting their dense

Climate Risks Across Germany[17]

Germany has undergone significant climate changes over the past century. Between 1881 and 2022, the annual average temperature rose by 1.7°C, with summer temperatures increasing by 1.58°C and winter temperatures by 1.72°C. The decade from 2011 to 2020 was 2°C warmer than the 1881–1910 period, with Western Germany warming faster than the East. Annual sunshine duration also rose by 9 % since 1951, intensifying temperature extremes.

Rainfall patterns have shifted, with annual precipitation increasing by 8 % from 1881 to 2020 and winter precipitation rising by 27 %, particularly in Western Germany. In contrast, summer precipitation decreased by 4 %. Projections indicate heavy rainfall events will intensify across all seasons, with increases of up to 45 % in some regions. Northern Germany, for instance, could see extreme rainfall events rise by 30 % for centennial events.

Flooding, driven by extreme rainfall, remains a major concern as urban hydrological systems are often overwhelmed, causing urban floods. Such events highlight the need for adaptive infrastructure to manage severe precipitation impacts. Storm activity is projected to increase, with the North Atlantic storm track shifting toward Europe. While the overall number of cyclones may not rise, stronger cyclones and high-wind events are expected, placing additional strain on urban transport systems.

Hail and severe thunderstorms also pose significant risks, as Germany is Europe's most hail-affected country. These trends demonstrate the urgent need for resilience-building measures to protect Germany's urban mobility infrastructure from escalating climate threats.

populations[17]. Extreme heatwaves and heavy rainfall-induced flooding are predicted to have particularly severe consequences for urban dwellers, heightening public health risks and straining critical infrastructure systems[18].

Rapid urbanisation and the expansion of built-up areas amplify these challenges. Urban densification, often a response to space constraints, intensifies the urban heat island effect, exacerbates air pollution, and increases infrastructure vulnerability to extreme weather events. This convergence of urban growth and climate change creates a feedback loop, where rising temperatures and pollution further degrade urban living conditions while infrastructure resilience struggles to keep pace with escalating climatic threats[17]. Three key extreme weather events pose particularly severe challenges for urban mobility both in Germany and China[18]:

Extreme Heat: Rising temperatures place significant stress on urban transport systems. Heatwaves cause thermal expansion of infrastructure, deforming roads and rails and leading to potential failures. In urban areas, where public transport vehicles are often overcrowded or poorly ventilated, extreme heat exacerbates health risks such as heat exhaustion for commuters. The increased demand for cooling systems also strains power grids, potentially disrupting electric-powered transport networks and further complicating mobility.

Extreme rain: Intense rain events overwhelm urban drainage systems, triggering flash flooding that inundates roads, railways, and pedestrian pathways. Prolonged waterlogging weakens road foundations, damages transit infrastructure, and causes signal failures in rail systems. These disruptions not only impede daily mobility but also hinder emergency response efforts, exacerbating socio-economic impacts and prolonging recovery times.

Storms: High winds and intense rainfall during storms directly threaten urban mobility. Fallen trees, debris, and power outages frequently halt public transport operations, while wind damage to infrastructure such as bridges, overhead lines, and

Deep Dive: Extreme Weather and E-Mobility

Electric vehicles (EVs) are a cornerstone of the transition to sustainable urban mobility, offering significant potential to reduce greenhouse gas emissions and improve urban air quality. In China, EVs are considered as a key lever to mitigate local pollution and contribute to regional and nationwide climate goals. However, the rapid adoption of EVs also exposes vulnerabilities in their supporting infrastructure, especially under the strain of extreme weather events exacerbated by climate change. Hydropower shortages, heatwaves, and other climatic shocks have already highlighted the risks posed to energy-resilient urban mobility systems, demonstrating the need for resilience-focused solutions.

As an example, the 2022 heatwave and drought in Southern China revealed critical weaknesses in e-mobility infrastructure, particularly in Sichuan Province, where 82 % of electricity comes from hydropower[27]. Severe drought reduced hydropower capacity by half, leading to widespread power shortages and the temporary closure of public EV charging stations[28]. In response, State Grid, China's largest utility company, offered up to 50 % discounts for off-peak charging to encourage nighttime use[28]. Additionally, some charging stations reduced efficiency during peak hours, slightly increasing charging times to lower overall power demand. Despite these interventions, the decreased reliability of the charging network pushed some users to revert to fossil-fueled vehicles, exposing a significant trust gap in e-mobility during crises[29].

This situation highlights the urgent need for resilient e-mobility systems capable of maintaining service even under extreme conditions to further be able to achieve Chinas ambitious sustainability goals regarding urban transport. Proposed solutions include integrating energy storage systems that feed electricity back into the grid during shortages. Whilst the technology remains in its early stages, it holds promise for enhancing grid stability[30]. Yet, the vulnerability of e-mobility infrastructure is intrinsically tied to the overall resilience of urban energy grids, calling for the implementation of advanced technologies like dynamic line rating and advanced power flow controls to optimise electricity distribution to ensuring stable power for critical systems[31].

bus shelters increase repair costs and delays. Urban areas lacking storm-resilient infrastructure face prolonged recovery periods, particularly in regions where design standards have not yet adapted to changing climatic conditions.

3. Impacts of Extreme Weather Events on Urban Mobility

The relationship between urban mobility and climate-induced extreme weather events can be examined through two key lenses: the demand side and the supply side. On the demand side, climate change impacts the behaviour and choices of commuters, shaping their preferences and ability to access transport systems. The supply side, on the other hand, refers to the capacity of urban mobility systems and infrastructure to deliver services reliably under changing climatic conditions. This section explores how extreme heat, heavy rainfall, and storms affect both dimensions of urban mobility, revealing the interdependencies between infrastructure resilience and user behaviour.

Extreme Heat

Demand	Supply
Extreme heat diminishes the comfort and safety of public transport. Without adequate cooling systems, vehicles become unbearably hot, deterring ridership and posing significant health risks for vulnerable populations, such as the elderly, children, and those with pre-existing health conditions. Discomfort may drive individuals toward air-conditioned private vehicles, increasing traffic congestion and exacerbating urban heat island effects. Public transport systems may also face increased operating costs due to higher energy consumption for air conditioning, potentially leading to fare hikes that discourage ridership.	High temperatures directly impact the physical infrastructure of urban mobility. Rail tracks buckle, asphalt softens, and roads crack under prolonged heat, requiring frequent repairs and disrupting services. The increased energy demand for cooling public transport systems and facilities can strain power grids, heightening the risk of blackouts that further interrupt operations. Material degradation accelerates under extreme heat, shortening the lifespan of infrastructure and increasing long-term maintenance costs.

Extreme Rain

Demand	Supply
Heavy rainfall disrupts daily commutes by causing delays, cancellations, and reduced service frequencies. Commuters may face extended wait times and overcrowding, particularly in poorly managed transit hubs, leading to dissatisfaction with public transport services. Safety risks, such as poor visibility and slippery conditions, further deter the use of public transport, pushing commuters to seek alternative travel options. Severe flooding may strand passengers, creating accessibility challenges and increasing reliance on emergency services.	Flooding caused by extreme rainfall inflicts significant damage on transport infrastructure. Roads may be undermined, bridges weakened, and tunnels flooded, leading to service disruptions that last for days or even weeks. Overwhelmed drainage systems exacerbate these impacts, creating persistent waterlogging in urban areas. Maintenance and repair activities are often delayed due to continuing adverse weather, accelerating infrastructure deterioration and driving up costs for municipalities.

Storms

Demand

Storms, with their high winds, flooding, and debris, lead to severe disruptions across all modes of transport systems. Public transit routes may become inaccessible, with blocked roads and damaged infrastructure preventing regular operations. Commuters face increased safety risks, such as accidents caused by falling debris or impaired visibility, further discouraging the use of public transport during and after storms. Emergency transport systems often become overwhelmed during storm events, delaying evacuations and rescue operations.

Supply

Storm damage to transport infrastructure can be extensive, including roads, bridges, transit stations, and power lines. These disruptions often require prolonged recovery periods and significant financial investments. Repeated storm-related damage weakens transport networks, making them increasingly vulnerable to future extreme weather events (2). Additionally, insurance and repair costs associated with storm damage divert funds from other critical urban needs, further straining urban mobility systems.

4. Case Studies: Solutions from China

In recent years, China has started to proactively enhance the resilience of its transport infrastructure to counter the challenges posed by climate change and extreme weather events. A notable initiative is the "sponge city" program, which integrates green spaces, permeable pavements, and sustainable urban drainage systems to manage stormwater and mitigate flooding[19]. Cities like Wuhan and Chongqing have implemented these strategies to bolster urban flood resilience. Additionally, China has incorporated climate adaptation into its national development strategies. The National Climate Change Adaptation Strategy emphasises integrating climate resilience into infrastructure planning, design, construction, and operations[20]. With this approach, China aims to ensure that transport systems are better equipped to withstand climate-related hazards. Furthermore, investments in climate-resilient infrastructure have been accelerated. However, reports indicate that enhancing infrastructure resilience to climate change in China faces an annual funding gap of nearly 500 billion Yuan over the next five years, highlighting the significant financial commitment required[21].

Extreme Rain

Rain Warning System in Guangdong

Guangdong's "31631" progressive rain warning system improves safety and preparedness during extreme weather by providing clear, timely updates. The system's timeline includes: 3 days in advance, a general forecast is issued; 1 day before, affected areas and timeframes are identified; 6 hours prior, high-risk zones are pinpointed; 3 hours in advance, these areas are refined; and 1 hour before, specific streets are named. Automated measures, such as school and workplace closures, further reduce risks and unnecessary mobility, ensuring a reliable and effective response to severe weather[22].

Advanced Information System Shanghai

Shanghai's Advanced Information System, managed by the Shanghai Flood Control Information Center, collects real-time data from a network of over 400 monitoring points, including sea-level, tide, meteorological, and drainage stations, with updates every five minutes. For example, drainage monitors trigger alerts at 20 cm water levels, escalating to road closures when levels exceed 30 cm. The system also keeps the public informed through platforms like Weibo and mass text messages. By delivering transparent, timely updates, the system mitigates risks, prevents the spread of rumors, and strengthens disaster preparedness in the city during natural disasters[23].

Extreme Heat

Water-Mist Bus Stops in Chongqing

Located in the Yangtze River Delta, Chongqing, home to over 30 million people, experiences prolonged heat waves with temperatures reaching up to 37 degrees Celsius. To provide relief for passengers waiting for public transport during these scorching days, the city has equipped its bus stops with water misters. These misters spray fine clouds of water cooled to 5–7 degrees Celsius, effectively reducing the waiting area's temperature to a more comfortable level[25].

Smart Subway Lines in Tianjin

Tianjin's Metro Line 6 incorporates innovative solutions to address the challenges of urban heat. Equipped with variable frequency heat pump air conditioning, the system dynamically adjusts cooling levels based on real-time temperature data. Advanced sensors throughout the metro monitor environmental conditions, such as temperature, humidity, and air quality, providing real-time data to the central control system. As soon as temperatures exceed 25 degrees Celsius, the system cools down to 22 degrees. Its functionality is reportedly extending to 40 degrees and beyond.[24] This enables precise climate control within the trains and stations, improving energy efficiency while maintaining passenger comfort[26].

China's multifaceted approach to building resilience into urban transport, ranging from releasing national policies "National Climate Change Adaptation Strategy 2035" to its concrete implementation by selecting 39 cities for "Deepening the Construction of Climate Resilient Cities" can serve as a compelling model for resilient urban transport systems of the future.

Whilst the Chinese Ministry of Natural Resources (MNR) is the main institution responsible for integrating climate aspect into existing urban spatial planning and issuing respective guidelines to adapt key indicators accordingly, including improving spatial connectivity and accessibility for urban mobility planning, it closely interacts with the Ministry of Ecology and Environment (MEE) in charge of designing low-carbon and resilient policies and accelerating the reconstruction of eco systems in city areas. Various research institutions and universities, such as the Territorial and Spatial Planning Institute under MNR and National Center for Climate Change Strategy and International Cooperation (NCSC) under MEE, further collect and analyse data, engage in scenario-building and risk assessment and derive respective recommendations for more climate-resilient urban and transport policy-making from the perspectives of urban spatial planning, environment and ecology. From China's strategy, three key takeaways can be derived to enhance urban transport resilience in the face of extreme weather events:

1. The importance of coordination and bundling of transport and weather data: establishing a common data pool shared by local governments, transit agencies, and meteorological services can facilitate proactive communication and planning. For instance, Germany could incorporate real-time weather information from the Deutscher Wetterdienst (DWD) into public transport apps, enabling automated route diversions and clear public warnings ahead of extreme weather.
2. The need for standardised "first response" measures. Automated protocols – such as closing schools once a predetermined storm or heat threshold is reached – would safeguard vulnerable populations and ensure consistency in emergency reactions.
3. Adopting a forward-thinking mindset when designing and upgrading infrastructure means embedding resilience at every stage. Much like China's permeable pavements and flood-adapted drainage systems, German cities could reinforce critical assets (e. g., rail bridges, overhead lines, and bus stations) to withstand strong winds and torrential rain.

By prioritising robust data-sharing frameworks, standardized first-response protocols, and climate-adaptive infrastructure, Germany and other urban centres can strengthen their capacity to protect citizens, maintain economic stability, and uphold public well-being in an era of intensifying extreme weather events.

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