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REVIEW

Climate adaptation of transport infrastructure to extreme heat and flooding

Adaptación climática de la infraestructura de transporte al calor extremo y las inundaciones

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ABSTRACT

Transport infrastructure is exposed to two accelerating climate hazards, extreme heat and flooding. This narrative review synthesizes evidence published between 2013 and 2025 on how roads, railways, bridges and public transport systems are adapted to these hazards. Extreme heat reduces rail capacity through track buckling and speed restrictions and accelerates pavement deterioration, while flooding disrupts road and rail networks and inundates underground transit systems. Assessment relies on multi-hazard fragility, GIS risk mapping and network metrics, increasingly combined with accessibility and equity criteria. Adaptation spans heat-resilient pavements, drainage and barrier upgrades, recovery scheduling and adaptation pathways, although uptake across governments remains uneven. Heat and flood burdens fall more heavily on low-income, older and informal transport users, and adaptation without explicit equity criteria risks widening transport disadvantage. A persistent gap remains between available engineering measures and their routine implementation, and between risk assessment and the social distribution of adaptation benefits.

Keywords: climate change adaptation; transport infrastructure; extreme heat; flooding; climate resilience; risk assessment.

RESUMEN

La infraestructura de transporte está expuesta a dos amenazas climáticas que se aceleran, el calor extremo y las inundaciones. Esta revisión narrativa sintetiza la evidencia publicada entre 2013 y 2025 sobre cómo se adaptan las carreteras, los ferrocarriles, los puentes y el transporte público a estas amenazas. El calor extremo reduce la capacidad ferroviaria por pandeo de vías y restricciones de velocidad y acelera el deterioro del pavimento, mientras que las inundaciones interrumpen las redes viarias y ferroviarias e inundan los sistemas subterráneos. La evaluación se apoya en fragilidad multiamenaza, cartografía de riesgo SIG y métricas de red, cada vez más combinadas con criterios de accesibilidad y equidad. La adaptación abarca pavimentos resistentes al calor, mejoras de drenaje y barreras, programación de la recuperación y rutas de adaptación, aunque su adopción entre gobiernos es desigual. Las cargas del calor y las inundaciones recaen más sobre usuarios de bajos ingresos, mayores e informales, y la adaptación sin criterios explícitos de equidad puede ampliar la desventaja de transporte. Persiste una brecha entre las medidas disponibles y su aplicación rutinaria, y entre la evaluación del riesgo y la distribución social de los beneficios.

Palabras clave: adaptación al cambio climático; infraestructura de transporte; calor extremo; inundaciones; resiliencia climática; evaluación del riesgo.

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INTRODUCTION

Transport infrastructure underpins daily mobility, freight supply and emergency access, yet its design standards are anchored in historical climate rather than the conditions the assets will experience over their service life. Two hazards dominate the adaptation agenda: extreme heat and flooding. Heat waves buckle railway track, soften asphalt and overheat signalling and rolling stock, while river, pluvial and coastal flooding closes roads, scours bridges and inundates underground networks.

Projections indicate that record-breaking heat and precipitation will expose a growing share of global rail and road assets, which moves adaptation from a marginal concern toward a core obligation for asset owners and transport agencies.(1,2)

Evidence on transport adaptation is dispersed across civil engineering, risk science, geography and transport studies, and it is advancing on two fronts at once. Assessment has moved from single-asset fragility toward network-level vulnerability, accessibility and equity, while adaptation practice has expanded from engineering measures toward pathways, governance and the social distribution of benefits.

Recent syntheses address road adaptation measures and underground systems separately,(3,4)but few reviews integrate heat and flooding across modes, and fewer still connect infrastructure adaptation to its social consequences.

A synthesis that links these strands is timely for the transport planning community, particularly because adaptation decisions taken now will determine the resilience of networks for decades.(5,6) The stakes are both economic and social, since transport failures during heat waves and floods disrupt labour markets, health access and emergency response.(7,8)

The objective of this review is to synthesize published evidence on the adaptation of transport infrastructure to extreme heat and flooding. The synthesis addresses six questions, organized as thematic axes: what are the direct impacts of heat, what are the direct impacts of flooding, how are vulnerability and risk assessed, which asset-level measures exist, how are adaptation planning and governance advancing, and how are benefits and burdens distributed across social groups. The review is narrative in design and does not claim exhaustive coverage.

DEVELOPMENT

Of the 77 retained studies, 10 addressed extreme heat impacts, 18 addressed flood impacts, 15 addressed risk and vulnerability assessment, 11 addressed asset-level engineering measures, 13 addressed network planning and governance, and 14 addressed equity and social dimensions, with several studies contributing to more than one axis.

The synthesis of the corpus by axis is presented first (Table 1). The evidence is strongest and most quantitative for flood impacts and network assessment, and thinnest for the equity outcomes of adaptation. The counts that follow describe the composition of the evidence base produced by the search and selection criteria rather than a census of the entire literature.

Table 1. Synthesis of the reviewed evidence by thematic axis.

Thematic axis	Key findings	Studies (n)	Representative studies
Extreme heat impacts	Rail buckling and speed restrictions; pavement softening and faster deterioration	10	(1) (2) (9) (10)
Flood impacts	Network-scale road and rail disruption; bridge scour; inundation of underground systems	18	(11) (12) (13) (14)
Risk and vulnerability assessment	Multi-hazard fragility, GIS risk mapping, network metrics with accessibility and equity	15	(15) (16) (17) (8)
Asset-level engineering	Heat-resilient pavements, drainage and barrier upgrades, recovery scheduling	11	(10) (11) (18) (19)
Network planning and governance	Adaptation pathways, stress testing, uneven policy uptake	13	(6) (20) (21) (5)
Equity and social dimensions	Unequal heat and flood exposure; heavier burdens on low-income and older users	14	(22) (23) (24) (25)

The core of the corpus is summarized by study design, region and finding in the matrix below, which lists representative studies for each hazard and mode (Table 2). Engineering and risk modelling studies dominate the corpus, while empirical studies of social outcomes are fewer and lean toward qualitative designs. The dominance of modelling reflects the difficulty of observing network-scale failures directly, but it also means that many quantitative results remain conditioned on assumptions that are only beginning to be validated.

Table 2. Representative core studies by design, region, infrastructure and hazard.

Study	Design	Region and context	Infrastructure and hazard	Key finding
Global rail and road exposure (1)	Exposure modelling with CMIP6	Global	Rail and road, heat and precipitation	Exposure to record-breaking extremes rises with warming
European roads and railways heat risk (2)	Scenario risk assessment	Europe	Road and rail, heat	Heat-related disruption risk increases with global warming
United States railroad connectivity (26)	Network analysis	United States	Rail, heat	Extreme heat threatens connectivity and ridership
London Underground heat delays (9)	Empirical delay analysis	United Kingdom	Underground rail, heat	High temperatures increase delays on the Underground
Climate-resilient asphalt design (10)	Literature review	Global	Road pavement, heat	Binder and mix adaptation improves heat resilience
Road adaptation to flooding (11)	Review of measures	Global	Roads, flooding	Pre-construction and post-event measures raise resilience
European road network flood robustness (12)	Network robustness model	Europe	Roads, river flooding	Networks withstand floods up to a tipping threshold
Bridge flood resilience (13)	Restoration modelling	Regional	Bridges, flooding	Restoration time quantifies bridge flood resilience
Dawlish coastal railway (27)	Case study	United Kingdom	Coastal rail, sea-level rise	Repeated damage shows coastal rail exposure and cost
Underground space flood resilience (14)	Review	Global	Underground systems, flooding	Integrated measures proposed for underground flooding
Chengdu metro flood risk (17)	Probabilistic GIS	China	Metro, flooding	Station-level flood risk ranking for the network
Dakar mobility resilience (22)	Mixed methods	Senegal	Road and informal transport, flooding	Flooding burdens poor and informal transport users
Heat exposure in public transit (23)	Exposure measurement	Multi-city	Public transit, heat	Riders are exposed to elevated heat during journeys
Active transport adaptation barriers (25)	Policy analysis	United States	Walking and cycling, heat	Barriers persist to heat adaptation for active travel

Note: CMIP6 = Coupled Model Intercomparison Project Phase 6; GIS = geographic information system.

Extreme heat impacts on transport infrastructure

Of the 10 studies that addressed extreme heat impacts, three projected future exposure of rail and road assets to record-breaking temperatures and found that exposure grows with each increment of warming.(1,2,26)

One global assessment using Coupled Model Intercomparison Project data concluded that both rail and road infrastructure face larger losses under record-breaking heat and precipitation events than under historical extremes.(1)

In another of them, the risk of heat-related disruption to European roads and railways was estimated to increase most steeply as global warming proceeds.(2)These exposure studies share a scenario logic but differ in spatial scale, from global grids to single national networks.(26)

Four of the 10 heat studies documented how high temperatures degrade railway track. Two of them analysed thermal stress and buckling mechanisms and showed that longitudinally coupled slab tracks respond nonlinearly to heat waves and that ballast degradation lowers the temperature at which buckling begins.(28,29)

One network case study recorded the hottest July day on a national railway and described the operational limits imposed on services.(30)The mechanical evidence converges on thermal expansion as the controlling failure mode, and it is consistent with the operational finding that capacity is reduced before failure occurs.

In two of the 10 studies, heat effects on rail operations and demand were measured directly. One empirical analysis of the London Underground linked high temperatures to increased delays.(9) One network study for the United States projected that extreme heat reduces railroad connectivity and ridership, with losses concentrated on lines without alternative capacity.(26)When restricted to operational evidence, both studies indicate that the service disruption of heat is transmitted through speed restrictions rather than through track failure alone.

Three of the 10 studies addressed asphalt pavements. One comprehensive review proposed climate-resilient pavement design through binder and mixture adaptation.(10)

Two field and design evaluations showed that cool pavements and nature-based surface materials reduce surface temperature and heat accumulation in hot climates.(31,32)The pavement evidence is consistent on the direction of the effect but thinner on long-term durability than the rail literature.

The heat studies also reveal a coupling between transport adaptation and urban heat mitigation. Cool pavements and shaded corridors reduce surface and air temperature, so a measure chosen to protect the asset also lowers the thermal load on pedestrians and riders.(31-33)This coupling allows heat adaptation of roads and public space to be evaluated against two outcomes, structural performance and thermal comfort, which several studies now do jointly.(32,33)

The heat studies diverge on the thresholds at which disruption begins. The operational analyses express thresholds as air or rail temperature and tie them to speed restrictions, whereas the mechanical studies express them as track buckling temperature and stress state.(9,29,30)

This difference in threshold definition complicates the transfer of disruption functions from one network to another and explains part of the variation in reported sensitivity across the axis.

Among the 10 heat studies, the main gap concerns field validation. Exposure and mechanical models outnumber observed damage records, and the delay functions estimated for a single network have not been transferred and tested elsewhere.(9,30)

This limits confidence in quantitative predictions even though the qualitative direction of heat impacts is well established.

Flood impacts on transport infrastructure

Of the 18 studies that addressed flood impacts, six examined network-scale disruption and showed that flooding closes roads and railways across wide areas rather than at isolated points.(11-13,34-36)

In one of them, European road networks were robust to river floods up to a tipping threshold, beyond which disruption cascaded across the network.(12)

One review of road adaptation organized flood measures by the time of intervention relative to the hazard.(11)The network studies agree that the spatial structure of a network, not only the flood depth at single assets, determines the total disruption.

Five of the 18 flood studies focused on bridges and found that scour and inundation are the dominant failure mechanisms. Two of them quantified restoration and resilience through analytical models and GIS-based risk indices.(13,35)

One invited perspective identified validation of fragility curves as a priority for improving bridge flood resilience.(36)Among these studies, the evidence agrees that bridge-specific assessment outperforms generic road network proxies for flood risk, and that restoration time is a workable resilience metric.(13)

Seven of the 18 studies examined underground and metro systems and documented inundation, cascading failure and slow recovery during extreme rainfall.(14,37-42)In one of them, the New York City subway was shown to face rising coastal storm-induced flooding risk under climate change.(38)

Two case studies of the Shanghai and Zhengzhou networks ranked stations and lines by flood risk and resilience.(39,40)

When restricted to operational systems, the studies converge on station entrances and ventilation shafts as the critical entry points for flood water.(14,37)

Three of the 18 studies addressed coastal corridors and pluvial damage to road surfaces and drainage. One long-standing case documented repeated damage to the Dawlish coastal railway in England from sea-level rise and the cost of maintaining the line.(27)Two engineering assessments showed that pluvial flooding damages pavement and that climate-informed design storms are needed for road drainage.(19,43)

In one of them, adaptation measures for pluvial flooding were evaluated for urban transport in Bangkok.(44)

The flood studies diverge on the outcome they measure. Network robustness studies express flood impact as the fraction of the network that remains connected, whereas bridge studies express it as restoration time or fragility.(12,13,35)

The two traditions are not integrated in a single model in the reviewed studies, so the network consequence of bridge failure is inferred rather than simulated.(36)This separation explains why comparable flood events produce such different reported impacts across the axis.

Flood impacts also propagate beyond transport into interdependent infrastructure. Two studies of underground and metro systems noted that flood water reaches energy, signalling and communications assets together with the transport tunnels themselves.(14,37)

This interdependence lengthens recovery because restoring a flooded network depends on the repair of utilities that are equally affected.(37,45)

One further study mapped flood susceptibility across a railway network to target resilience investment, which illustrates the transition from impact description to risk-informed prioritization.(46)Among the 18 flood studies, the remaining limitation is metric heterogeneity: flood depth, return period and exposure are defined inconsistently, which constrains direct comparison of magnitudes across the axis.

Risk and vulnerability assessment

Of the 15 studies that addressed risk and vulnerability assessment, four established multi-hazard fragility and network-level metrics as the dominant approach.(15,47-49)One widely cited review defined fragility of transport assets under multiple hazards as the foundation for infrastructure resilience.(15)

One GIS-based framework delivered high-level climate risk assessment for critical infrastructure, including transport.(47)These studies anchor the assessment literature and provide the language of fragility curves and network metrics that the applied studies reuse.

Four of the 15 assessment studies applied GIS-based hazard, vulnerability and risk mapping, including to metro systems.(16,17,50,51)In one of them, a probabilistic framework ranked metro stations in Chengdu by flood risk.(17)

One methodological framework standardized flood hazard assessment for land transport infrastructure.(51)Among these studies, the mapping workflow is reproducible, but data availability constrains its transfer to lower-income settings.(16)

Four of the 15 studies used statistical and data-driven models to quantify flood probability and network resilience.(41,52-54)In two of them, flood probability for roads was estimated from spatial-statistical and watershed characteristics.(52,54)

One study predicted the resilience of transport infrastructure to natural disasters with a proportional hazards model.(53)When restricted to data-driven approaches, the evidence is strongest where long flood records exist and weaker for future regimes.

Four of the 15 studies combined criticality, accessibility and socio-economic exposure to prioritize adaptation.(8,49,55,56)

In one of them, road adaptation interventions were prioritized by combining flood risk with network criticality and socio-economic data.(55)

One city assessment for Cape Town linked climate impact to transport infrastructure risk.(56) These studies converge on the conclusion that risk ranking changes when accessibility and equity enter the objective function.(8)

The assessment studies diverge on data requirements. Probabilistic and data-driven models need long flood and failure records, which are available mainly in well-instrumented networks, whereas GIS-based mapping can proceed with open elevation and exposure data.(16,17,52)This divergence has a geographic consequence: the most data-intensive methods cluster in high-income networks, while lower-income settings rely on simpler screening tools.(16,56)

Two further studies extended assessment toward dynamic and cascading analysis. One digital twin framework integrated real-time data for city-scale flood impact analysis,(57)and one study deduced flood disaster chains from cascading failures in urban critical infrastructure.(45)

These emerging approaches move assessment from static exposure toward the propagation of disruption, which the network studies had identified as decisive.(12)

Asset-level engineering adaptation

Of the 11 studies that addressed asset-level engineering measures, four examined road flood adaptation and found that measures span pre-construction design, drainage upgrades and post-event recovery.(11,19,43,58)

One rational framework organized post-flood road network recovery by condition and priority.(58)Two engineering assessments connected climate-informed design storms to drainage capacity and pavement resilience.(19,43)

The road literature is distinctive in treating adaptation as a lifecycle question that begins at design and extends through recovery.

Three of the 11 engineering studies addressed heat-resilient pavements and converged on binder modification and cool surface materials as the principal levers.(10,31,32)

In one field evaluation in San Antonio, cool pavement reduced surface temperature as an urban heat mitigation measure.(31)One study in extremely hot climates proposed nature-based cool pavements to reduce heat stress.(32)Among these studies, the evidence supports surface cooling, while long-term structural durability remains less documented.

Four of the 11 studies examined underground and metro adaptation and showed that drainage upgrades, protective barriers and recovery scheduling are complementary.(4,18,44,59)One review characterized the impact of climate change on underground transport infrastructure and the measures available.(4)

One optimization case study scheduled recovery resources to enhance flood resilience of urban rail transit in London.(18)When restricted to implemented measures, the evidence is thinner than for proposed measures, and most studies evaluate a single intervention on a single network.(59)

The engineering studies also distinguish retrofit from new construction. Pre-construction design changes are cheaper and easier than retrofitting existing assets, so the review evidence favours embedding adaptation in renewal cycles rather than treating it as a separate retrofit programme.(6,11)

Recovery frameworks extend the same logic to the aftermath of flooding, where condition-based prioritization determines how quickly the network returns to service.(58)

Three of the 11 studies signalled a shift toward nature-based and green drainage measures. Cool and nature-based pavements reduce heat and runoff together, and drainage adaptation for mass rapid transit increasingly pairs grey pipes with green retention.(32,44,59)

These measures offer co-benefits for heat and flood but are evaluated mainly for single hazards, which leaves their combined performance under compound events untested.(44)

Across the 11 engineering studies, cost-effectiveness is the weakest element. The measures are technically defined, but comparative costs and benefits remain unquantified in the reviewed studies, which leaves asset owners without a clear basis for choosing among them.(11,31)

The optimization studies begin to address this gap for recovery scheduling, but not yet for construction and maintenance decisions.(18)

Network-level adaptation, planning and governance

Of the 13 studies that addressed planning and governance, three framed adaptation as business as usual through asset management.(3,6,60)

One framework proposed climate-change-ready transport infrastructure in which adaptation is embedded in routine management.(6)

One systematic review catalogued adaptation measures for road transport infrastructure.(3)In one of them, adaptation investment trends for transport resilience were identified across regions.(60)

Four of the 13 governance studies addressed prioritization and investment using robustness, accessibility and stress testing.(55,61-63)

One accessibility-based comparison assessed road network resilience across scenarios.(61) One methodology prioritized simulation-based stress tests for transport resilience without full computation.(62)A regional case study in southeast Australia evaluated resilience investments under climate change.(63)

Three of the 13 studies promoted adaptation pathways and flexible strategies for coastal and rail systems under uncertainty.(20,64,65)

In one of them, adaptation pathway approaches were informed for vulnerable coastal infrastructure.(20)One resource-aware framework optimized climate-resilient railway networks.(64)One study proposed flexible adaptation for compound climate risks in port infrastructure.(65)

Three of the 13 studies evaluated policy uptake and found that adaptation remains uneven across governments.(5,21,66)In one of them, climate change adaptation policies for urban transportation in India were assessed against implementation criteria.(21)

One review of climate-resilient mobility identified emerging trends and persistent challen-

ges.(5)One further study confirmed that transportation networks remain vulnerable to climate disruptions despite planning advances.(67)

The governance studies diverge on where adaptation succeeds. Framework and pathway studies emphasize national and network-scale planning, whereas policy evaluations find that adoption stalls at the level of funding, maintenance regimes and institutional mandates.(6,20,21)This divergence suggests that the content of adaptation plans is less binding than the budget and organizational authority attached to them.(60)

The governance evidence converges on a gap between framework availability and routine adoption. The instruments exist, but the studies that track implementation find them used selectively and unevenly across modes and regions.(5,21,67)This gap is the central policy finding of the axis and reappears in the equity discussion below.

Equity and social dimensions of adaptation

Of the 14 studies that addressed equity, four measured unequal heat exposure in transit and pedestrian environments.(23,24,68,69)In one of them, exposure to extreme heat in public transit systems was quantified across journeys.(23)

One study found an unequal distribution of urban street shading in Shanghai.(68)When restricted to exposure measurement, the studies agree that heat burdens track neighbourhood disadvantage.(24)

Four of the 14 equity studies examined active transport adaptation and found that shading, tree canopy and route choice reduce heat stress, with implementation barriers persisting.(25,33,70,71)One policy analysis identified barriers and facilitators for heat adaptation of active transportation in United States cities.(25)

Two microclimate and observational studies linked tree canopy to walking willingness and cycling heat risk.(70,71)In one of them, travel behavior and infrastructure change were both shown to mitigate heat exposure.(33)

Six of the 14 studies showed that flooding and heat alter travel behavior and accessibility, with heavier burdens on low-income, older and informal transport users.(8,22,72-75)In one mixed-methods study in Dakar, recurrent flooding exacerbated mobility challenges for poor residents and informal transport operators.(22)

One accessibility model incorporated extreme weather exposure into the cost of public transit access.(8)One study measured heat exposure among minibus taxi workers in South Africa and proposed interventions.(75)

One further study documented how bike-sharing use shifts during extreme weather events, which shows that adaptation of shared mobility depends on user behaviour as well as infrastructure.(76)

The equity studies diverge on the unit of analysis. Exposure studies measure heat or flood at the neighbourhood or journey level, whereas behavioural studies measure how users change travel in response.(23,69,72)

The two perspectives produce complementary but not interchangeable conclusions: exposure describes the hazard distribution, while behaviour describes the coping response, and the coping response itself varies with income and age.(22,74)

Three of the 14 studies argued that adaptation without explicit equity criteria risks reproducing or widening transport disadvantage.(24,25,68)

The equity evidence is consistent on direction but limited by cross-sectional designs and single-city samples, and it is the least developed part of the corpus in causal terms.

Synthesis across the six axes

Across the six axes, three patterns recur. Impacts are the best documented, assessment is the fastest-moving field, and response lags both in implementation and in equity measurement. The corpus shows a consistent migration of methods from static exposure toward network disruption and, more recently, toward the social distribution of risk.(8,15,48)

The migration of methods has a clear sequence. Fragility and GIS mapping established where assets are exposed, network metrics established how disruption propagates, and accessibility and cost models are now establishing who bears the consequences.(8,12,15)

Each step inherited the data and the vocabulary of the previous one, which is why the later stages remain the least developed in causal terms.(24)

The weak links are the same in every axis: field validation for heat, standardized flood metrics, cost-effectiveness for engineering, institutional authority for governance, and longitudinal designs

for equity.(11,21,24,31,36)

These weak links are not independent: the absence of field validation limits cost estimates, and the absence of longitudinal designs limits any claim about whether adaptation has reduced disadvantage.

DISCUSSION

The principal finding of this review is that transport adaptation has matured technically while lagging in routine implementation and in the equitable distribution of its benefits. Assessment methods are increasingly sophisticated and the engineering measures are available, yet the studies repeatedly locate the bottleneck in governance, financing and social distribution rather than in knowledge of what to build.(6,21,60)

The evidence on extreme heat is consistent across exposure, mechanical and operational studies. Global and regional projections agree that heat exposure grows with warming, and the engineering literature identifies buckling and pavement softening as the controlling mechanisms.(1,2,10,28)

This convergence contrasts with the flooding literature, where the evidence is broader but less standardized: studies use different flood metrics, return periods and network representations, which complicates direct comparison.(11-13)

The difference is explained by the physical clarity of heat failure modes relative to the hydraulic and hydrological uncertainty of flooding.

The assessment literature shows a clear evolution from single-asset fragility toward network and equity metrics.(8,15,48)

Earlier work treated fragility as the state of the art, whereas the more recent studies add accessibility and socio-economic weighting to the objective function.(49,55)

This shift is consistent with the transport planning literature on accessibility-based resilience and with the emerging emphasis on mobility justice.(5,61)

Discrepant findings are rare and mostly reflect whether equity criteria are included at all. Cascading and digital-twin approaches extend the same logic toward the propagation of disruption, which reinforces the network view rather than contradicting it.(45,57)

The engineering measures are the most mature part of the evidence base. Heat-resilient pavement, drainage upgrades, barriers and recovery scheduling are all technically defined and, in several cases, field evaluated.(10,18,19,31)

Yet the governance studies show that adoption remains uneven, which indicates that the binding constraint is institutional rather than technical.(5,21)

This gap between available measures and their deployment is the most policy-relevant result of the review and echoes earlier work on adaptation becoming business as usual.(6,77)

The implication for practice is that agencies would gain more from institutional integration than from further technical refinement of measures.

The applicability of the evidence varies by region. The operational case studies concentrate in European, North American and Chinese networks, where asset inventories, gauges and flood records are dense.(1,38,39)

The African and South Asian evidence is thinner and, where it exists, focuses on household and informal transport adaptation rather than on network assets.(22,72,75)This imbalance means that the strongest quantitative results may transfer least to the settings with the highest flood exposure and the weakest infrastructure.

One underdeveloped area is the compound hazard. Heat and flooding are treated as separate problems in nearly all studies, yet heat waves and intense rainfall can occur in sequence or jointly, and their effects on pavement, track and drainage interact.(1,65)

Only the port and coastal adaptation studies explicitly model compound climate risks.(65) This separation likely underestimates the true demand on transport systems in a warming climate.

The evidence also underlines the value of monitoring and evaluation. Adaptation pathways depend on signals that trigger the next intervention, and the pathway studies identify monitoring as the condition for their own success.(20,65)

Without routine condition and exposure data, agencies cannot know whether an intervention performed as intended, which returns the discussion to the field-validation gap identified in the Development section.(36)

Compared with earlier syntheses, this review finds that the field has moved from cataloguing measures toward evaluating their adoption and distribution. The road adaptation and underground

infrastructure reviews organize the field around measures,(3,4)whereas the recent equity and accessibility studies treat the distribution of outcomes as the central question.(8,24)

The two generations are complementary, but the shift in emphasis reflects the entry of transport and social science into a domain previously dominated by engineering.(5)

The equity findings add a dimension that most technical syntheses omit. Heat and flood burdens fall more heavily on low-income, older and informal transport users, and exposure tracks neighbourhood disadvantage.(22-24,75)

Adaptation framed only around asset condition would therefore reproduce existing disadvantage. This finding aligns with studies of heat risk inequality and with evidence on the barriers to active transport adaptation, but it is the least developed part of the corpus in terms of causal design.(24,25)

The social dimension deserves the same measurement effort that has been applied to fragility and network metrics, and the economic cost studies already offer a template for doing so.(7,8)

The level of evidence varies by finding. The direction of heat and flood impacts rests on convergent modelling and operational studies and can be treated as well established, whereas the causal effect of specific adaptation measures on user outcomes rests on single case studies and field evaluations with short horizons.(10,18,31)

Equity conclusions are supported in direction but not yet in magnitude, so they should be read as hypotheses for evaluation rather than as settled findings.(22,24)

Implications for practice

For asset owners, the clearest message is that the technical measures already exist and that the return on effort now lies in embedding them in routine maintenance and renewal cycles. Heat-resilient pavement, drainage upgrades and flood barriers can be adopted incrementally at points where assets are replaced, which the business-as-usual framing captures well.(6,10,11)

For planning authorities, the assessment evidence points toward network and equity metrics rather than single-asset fragility as the basis for prioritization.(8,48)

Ranking interventions by asset condition alone will underinvest in low-income areas where heat and flood exposure is concentrated, so accessibility and socio-economic weighting should enter the prioritization function from the start.(24,55)

For governments, the governance evidence is a caution against treating the publication of an adaptation plan as the endpoint. The studies that track implementation find that uptake depends on budgets and institutional mandates, and that without them even well-designed measures remain on paper.(5,21,67)

Financing mechanisms and evaluation routines are therefore as important as the engineering content of adaptation.

For operators of transit and active transport, the equity evidence implies that heat and flood adaptation should be co-designed with the users most exposed, particularly older riders, informal transport workers and residents of low-income neighbourhoods.(22,74,75)Measures such as shaded waiting areas and drainage at station entrances protect the same groups that currently bear the highest exposure.(23,25)

Limitations of the studies, the evidence and the review process

The studies themselves are limited by scale and design. Most exposure and network analyses rely on modelled hazards and generic fragility functions rather than observed damage, and the operational evidence is concentrated in high-income networks, particularly in Europe, the United States and China.(1,38,39)

Empirical studies from lower-income and informal transport settings remain scarce, which weakens the transferability of the results to the contexts where flood exposure is highest.(22,72)

The evidence base is also limited by heterogeneity. Flood studies use inconsistent hazard metrics and return periods, and cool pavement evaluations measure surface temperature rather than structural service life.(11,31)

These inconsistencies mean that the synthesis could compare directions of effect more reliably than magnitudes, and they argue for common reporting standards in transport adaptation research.

The review process itself has limits. The search was documented but not exhaustive, restricted to three bibliographic sources and to publications through 2025, and grey literature and institutional reports were not included.

Language coverage was limited to the English-language records retrieved by the databases,

and the assignment of studies to axes depended on the reviewers' reading of titles and abstracts. These choices could omit relevant non-English or technical-report evidence, so the axis counts should be read as indicative rather than as a census of the field.

Research agenda

Five concrete directions follow from this synthesis. First, bridge and metro fragility functions should be calibrated against observed flood damage rather than transferred across regions.(36) Second, heat and flood adaptation should be evaluated for structural service life and cost-effectiveness, not only for surface temperature or immediate disruption.(7,31)

Third, evaluation of adaptation should incorporate equity outcomes as a primary metric, following the accessibility and cost approaches that already exist.(8,24)

Fourth, studies from lower-income and informal transport contexts should be expanded so that adaptation guidance does not remain concentrated in high-income networks.(22,72)

Fifth, compound heat-flood events should be modelled explicitly so that measures designed for one hazard are tested against their interaction with the other.(1,65)

These directions would close the gap between the technical maturity of adaptation and its routine, equitable deployment.

CONCLUSIONS

The direct impacts of extreme heat on transport infrastructure were characterized by rail buckling, speed restrictions and pavement deterioration, while flooding was shown to close roads, scour bridges and inundate underground systems. Vulnerability and risk were assessed through multi-hazard fragility, GIS risk mapping and network metrics that increasingly incorporated accessibility and equity.

Asset-level adaptation offered heat-resilient pavements, drainage and barrier upgrades and recovery scheduling, yet network-level adoption remained uneven across governments. Planning and governance advanced toward adaptation pathways and stress testing, although implementation lagged behind available frameworks. Equity analyses showed that heat and flood burdens fell disproportionately on low-income, older and informal transport users. Adaptation that lacks explicit equity criteria therefore risks widening transport disadvantage rather than reducing it.

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