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REVIEW

Transport network resilience to climate shocks

Resiliencia de las redes de transporte ante perturbaciones climáticas

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ABSTRACT

Transport networks are exposed to a widening set of climate shocks, from river and pluvial flooding to sea level rise and extreme precipitation, yet the field lacks a consolidated account of how their vulnerability and recovery are measured. The review shows that metrics cluster into topological, performance-based and accessibility families, that flooding dominates hazard modelling through depth-disruption functions, and that efficiency and resilience can trade off within the same network. Recovery remains the least standardized dimension, with bridge restoration the most formalized component and equity considerations only recently incorporated. The evidence is predominantly simulation-based and case-study driven, with few validated, multi-hazard and dynamic assessments. Convergence across studies supports accessibility-based and hybrid metrics as the most informative for policy, while divergences stem from data availability, scale and the treatment of travel demand. The review concludes that standardized vulnerability and recovery metrics, validated against observed disruptions, and explicit distributional criteria are the principal needs for transport resilience research.

Keywords: transport network; resilience; vulnerability; climate change; infrastructure recovery; extreme weather.

RESUMEN

Las redes de transporte están expuestas a un abanico creciente de perturbaciones climáticas, desde inundaciones fluviales y pluviales hasta el aumento del nivel del mar y la precipitación extrema, aunque el campo carece de una síntesis consolidada sobre cómo se miden su vulnerabilidad y su recuperación. La revisión muestra que las métricas se agrupan en familias topológicas, basadas en desempeño y de accesibilidad, que las inundaciones dominan la modelización mediante funciones de profundidad-disrupción y que eficiencia y resiliencia pueden entrar en conflicto dentro de una misma red. La recuperación sigue siendo la dimensión menos estandarizada, con la restauración de puentes como componente más formalizado y las consideraciones de equidad incorporadas solo recientemente. La evidencia es predominantemente de simulación y estudios de caso, con pocas evaluaciones validadas, multirriesgo y dinámicas. La convergencia entre estudios respalda las métricas híbridas y de accesibilidad como las más informativas para la política, mientras que las divergencias proceden de la disponibilidad de datos, la escala y el tratamiento de la demanda de viajes. La revisión concluye que las principales necesidades de la investigación son métricas estandarizadas de vulnerabilidad y recuperación, validadas frente a disrupciones observadas, y criterios distributivos explícitos.

Palabras clave: red de transporte; resiliencia; vulnerabilidad; cambio climático; recuperación de infraestructura; fenómenos meteorológicos extremos.

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INTRODUCTION

Transport networks carry most of the daily mobility on which urban and regional economies depend, and they are exposed to a widening set of climate shocks. River and pluvial flooding, sea level rise, storm surges, heat and extreme precipitation damage roads, bridges and railways and interrupt the services they deliver.(1,2)

A global assessment estimated that about 27% of all road and railway assets are exposed to at least one natural hazard and about 7.5% to a 1/100-year flood event.(2)

Projections for Europe point in the same direction, with climate extremes expected to raise damage to critical infrastructure as warming intensifies.(3)

In coastal and flood-prone regions the risk is concentrated on a small number of assets whose failure propagates through the rest of the network.(4)

Bridges show the mechanism, because loss of a single crossing can cascade into large economic and social disruption across the systems they connect.(5)

The exposure of roads, railways, ports and underground spaces is therefore not a distant scenario but a present design constraint for mobility systems.(6)

The literature on this problem is dispersed across transport engineering, network science and risk geography, and it has grown without a shared vocabulary for vulnerability and recovery. Seminal discussions drew the boundary between vulnerability and resilience and tied both to network structure,(7,8)while comprehensive reviews catalogued performance measures used in disasters without settling on a standard.(9)

Freight applications showed early how preparedness, response and recovery could be optimized together, but that phased approach has not been generalized to passenger and public transport.(10)

Recent syntheses confirm that resilience metrics for road networks remain classified in competing ways and that dynamic, multi-hazard assessment is still uncommon.(11,12)

Maritime and shipping studies reached the same conclusion for another mode, which demonstrates that the fragmentation is systemic rather than specific to road transport.(13,14)

The same is true of strategic game-theoretic treatments, which remain separated from the metric and simulation literature despite addressing the same networks.(15)

The objective of this review is to synthesize the conceptual frameworks, vulnerability metrics and recovery measures applied to transport networks under climate shocks, and to identify the convergences, divergences and gaps in the evidence.

Three guiding questions structure the synthesis: how are vulnerability and recovery conceptualized and measured, how are climate hazards represented in disruption modelling, and what do the resulting assessments reveal about network behaviour and its consequences for adaptation. The synthesis is organized in five thematic axes and is explicitly narrative rather than systematic. The review covers road, rail, public transport and maritime networks, with emphasis on the measures that quantify vulnerability and recovery rather than on the engineering of individual assets.

DEVELOPMENT

Fifty-two studies published between 2013 and 2026 were assigned to five thematic axes (Table 1). Table 1 summarizes each axis, the number of supporting studies and the principal findings. The axes proceed from concepts and metrics to hazard representation, performance loss and recovery, which is also the order followed below.

Conceptual frameworks and definitions

Of the seven conceptual studies, three discuss the meaning and boundaries of resilience and vulnerability, three are reviews that map the field, and one contributes a methodological indicator. The distinction that prevails was articulated a decade ago: vulnerability describes the susceptibility of a system to a disturbance, whereas resilience describes its ability to absorb the disturbance and recover, and the two must be measured with different tools.(7,16)

In the same line, connectivity was proposed as the concept that joins network structure to both properties, because the number and arrangement of alternative paths condition how a shock is distributed across the system.(8)

Table 1. Synthesis matrix of the five thematic axes.

Axis	Studies (n)	Key findings	Level of evidence
Conceptual frameworks and definitions	7	Resilience and vulnerability are complementary properties; connectivity links structure to both; definitions remain non-standardized	Conceptual and review papers
Vulnerability metrics	11	Topological, performance and accessibility families coexist; hybrid measures are growing	Reviews and cross-sectional case studies
Representation of climate hazards	11	Flooding dominates through depth-disruption functions; multi-hazard and sea-level rise exposure is global	Empirical functions and continental risk assessments
Performance loss and cascading effects	11	Disruption propagates as congestion and accessibility loss; efficiency and resilience can trade off	Traffic simulation and network science
Recovery, restoration and adaptation	12	Recovery is the least standardized; bridge restoration is formalized; equity is only emerging	Restoration models and strategy assessments

Resilience is decomposed into capacities that can be quantified, and the corpus shows which of them are actually measured. The comprehensive review by Faturechi and Miller-Hooks organized performance measures around preparedness, response and recovery phases and showed that pre-event and post-event metrics are combined in a single assessment in only a minority of cases.(9)

A more recent methodology added the Link Performance Index for Resilience, which tracks both resistance and recovery of individual road sections from traffic observations.(17)

The capacities into which resilience is decomposed are drawn from the infrastructure literature, where robustness, redundancy, resourcefulness and rapidity are treated as the four measurable properties of a resilient system. No study in the corpus measures all four capacities at once, and the asymmetry is clear: robustness and redundancy appear in most topological analyses, whereas rapidity appears only in recovery models.(18)

This uneven adoption explains part of the divergence between metric families described in the next axis.

Definitions have also moved from static to dynamic. Early formulations treated resilience as the depth and duration of performance loss, an approach captured by the resilience triangle. More recent work adds adaptive capacity and transformation, so that a network is resilient not only when it returns to its previous state but when it can adjust to a changed climate.(19)

The shift matters for measurement, because dynamic definitions require time series of performance rather than a single static index.

The field-level syntheses confirm that the concepts are shared but the metrics are not. The systematic review of road network resilience classified existing measures into topological, functional and hybrid approaches and identified link-level assessment, dynamic traffic behaviour and multi-hazard interaction as the persistent gaps.(11)

The bibliometric study of vulnerability assessment reached a compatible conclusion at a global scale, documenting a field that is expanding in output but not consolidating around a standard.(20)

No study in this axis disputes that resilience is multidimensional. One study does caution that the role of connectivity can shift from protective to harmful depending on the type and location of the shock, which weakens any claim that more connections always mean more resilience.(8)

The limitation shared by the axis is that these definitions were developed largely for infrastructure in general and have only partially been adapted to the demand-side behaviour of transport users, whose travel choices redistribute the consequences of a closure.

Vulnerability metrics

Eleven studies quantified network vulnerability, and their measures separate into three families: topological, performance based and accessibility based (Table 2). Six of the eleven applied topological or robustness indices, which score links or nodes by their contribution to connectivity, criticality or percolation. Robustness was quantified for flood-prone road networks through preparedness, response and recovery components.(21)

National road network vulnerability was assessed globally with a topological index, allowing cross-country comparison of structural exposure.(22)

The effect of administrative boundaries on vulnerability was demonstrated across cities,

showing that network measures change when the analysis is confined to a municipal border.(23)

Robustness was also evaluated for coupled railway-road networks under typhoon disruption,(24)for road networks under projected sea level rise through a multi-strategy percolation framework,(25)and for Japanese cities in relation to urban form and city-level characteristics.(26)

The topological family is attractive because it needs only the network graph and no travel data, which explains its dominance in the corpus. The cost is that it treats every link as equally important to users, regardless of how many people actually depend on it. In k of these studies, the ranking of critical links was shown to change when the measure was replaced by another, which cautions against reporting a single index as definitive.(27)

The choice among families is in practice a choice about data. Topological indices require only the network graph, which can be assembled from open street data. Accessibility measures add land use, population and travel time, and performance measures add traffic counts or assignment models. The data burden rises from one family to the next, which explains why well-resourced cities contribute the richest assessments and why topological indices dominate in data-poor settings.(22,26)

Performance-based measures sit between the other two families in both data demand and interpretability. They require observed or modelled traffic, but they return quantities that decision-makers recognize immediately, such as added travel time or lost capacity.(28,29)

Their weakness is that a delay in minutes says nothing about who is delayed, which is why accessibility and capability measures remain necessary for distributional questions. Functional resilience studies occupy the middle ground. The Beijing subway analysis measured how the network responds to supply and demand disruptions without external intervention, using capacity dimensions that belong to neither a purely structural nor a purely traffic view.(28)

Such studies matter because public transport resilience cannot be read from link topology alone, yet they remain few relative to the topological corpus.

The remaining five studies of this axis are more heterogeneous. Functional resilience was measured for the Beijing subway through capacity-related dimensions that begin with robustness and extend to the network's ability to absorb supply and demand disruptions.(28)

Accessibility loss was compared for the road networks of Valencia and Sardinia under cumulative section removal in random and deterministic order, showing how territorial accessibility degrades as sections are eliminated.(30)

Table 2. Families of vulnerability metrics applied to transport networks.

Metric family	Representative measures	What the metric captures	Limitations
Topological	Connectivity loss, betweenness centrality, criticality, robustness index, percolation threshold	Structural exposure of links and nodes to removal	Ignores travel demand and user response
Performance based	Travel time, delay, capacity loss, congestion, functional resilience	Output loss of the system under disruption	Requires traffic or assignment data
Accessibility based	Change in reachable destinations, isochrone contraction, capability set	Spatial and social consequences of disruption	Needs land-use and network data
Hybrid	Resilience triangle, robustness and rapidity, depth-disruption functions	Resistance and recovery in one measure	Often calibrated at component level

When restricted to city-level comparisons, vulnerability correlates with urban form and boundary effects, so findings do not transfer directly from one national context to another.(23,26)

Two reviews close the axis by concluding that hybrid and accessibility measures are more informative for policy than purely topological ones, at the cost of heavier data requirements.(31,32)

The accessibility family is distinctive because it connects a closed link to the destinations and populations that become unreachable, which is the information most relevant to equity and to the prioritization of repairs. The convergence of the two reviews on this point, despite drawing on different corpora, is one of the most robust findings of the axis.

The accessibility family shades into capability-based measures when the outcome of interest is not the set of reachable destinations but the activities people can perform with that access. In the capability formulation used elsewhere in this review, a flooded road is relevant because it removes functionings, which a longer trip alone does not capture.(33)

The distinction is consequential for equity, because two residents of the same neighbourhood can lose different functionings from the same closure, depending on their mobility options and their daily obligations.

Representation of climate hazards

Of the eleven hazard studies, six concern flooding, four concern sea level rise and multi-hazard exposure, and one concerns cascading linear infrastructure. Flooding is the dominant hazard in the transport literature, and the depth-disruption function is its standard interface between hazard intensity and performance loss. That function, derived from an empirical review of vehicle behaviour in water, replaced the earlier binary treatment of flooded roads and allowed partial rather than complete closure to be represented.(34)

It was then embedded in a continental flood risk assessment of the European road network that combined road-specific damage functions with high-resolution exposure data from OpenStreetMap.(4)

Flood modelling has since been extended in three directions. Stability functions were integrated into transport flood risk frameworks to represent how vehicles lose control or float in moving water.(35)

Hydrodynamic and BIM-GIS detail was added to road flood risk assessment in a wadi catchment in Algeria, coupling the hazard model to the road geometry.(36)

Bridge-specific risk assessment combined GIS with remotely sensed data to capture the assets that dominate indirect losses.(37)

Multi-scenario flooding was also used to locate emergency management centres so that the network can be served when it fails.(38)

The depth-disruption function deserves a caveat. It was calibrated from observational and experimental studies of light vehicles in standing water, and its transfer to other vehicle types, to moving water and to rail remains an assumption rather than a measurement.(34)

Later work addressed part of this by adding stability functions for vehicles in flowing water.(35)The function nonetheless illustrates the wider pattern of the axis: hazard detail improves in steps, and each step is validated for one context before it is generalized.

Sea level rise and multi-hazard exposure move the analysis from single events to long-run risk. Global estimates show that road and rail exposure is widespread and unevenly distributed, which implies that adaptation priorities differ sharply across countries.(2)

At the European scale, climate extremes are projected to escalate infrastructure impacts as warming intensifies,(3)and frameworks were built for road vulnerability to sea level rise and sea storm surges.(39)

The coastal railway at Dawlish in England became the canonical case of how one exposed segment can sever an entire corridor and of the adaptation options that follow.(40)

Cascade risk across interdependent linear infrastructures was quantified separately, showing that indirect flood impacts travel beyond the directly flooded assets.(41)

The hazard studies differ sharply in spatial resolution. Continental assessments operate on aggregated assets and national exposure, whereas catchment and bridge studies resolve individual structures and their hydraulic behaviour.(4,37)

The trade-off is explicit: continental models cover the whole system but smooth local failure mechanisms, while local models capture mechanisms but cannot be generalized. Future climate adds a second layer of uncertainty, because sea level and storm surge projections enter the analysis as scenarios rather than as observations.(39,40)

No study in the axis addresses heat or extreme temperature at network scale, even though pavement and rail temperature effects are recognized in the asset literature. The omission indicates a gap relative to flood research rather than an absence of the hazard, and it means that current network models describe the wet side of climate change more completely than the thermal side.

Validation of hazard models follows the same uneven pattern as the metrics. Depth-disruption and damage functions are calibrated against experiments or past events in specific regions, and their use elsewhere is an extrapolation.(4,34)

Continental exposure maps are confronted with the observed failure of individual assets in only a few studies, so their resolution of local criticality remains an open question.(2)

Performance loss and cascading effects

Eleven studies assessed how climate shocks translate into network performance loss. Six of them modelled traffic disruption, congestion or delay propagation under flooding or extreme rainfall. In the San Francisco Bay Area, integration of a traffic model with flood maps showed that closure of flooded roads produces employee absences and delays whose effects cascade into surrounding communities.(42)

Equivalent results were reported for flooding propagation in urban networks,(43)for dynamic

congestion risk under flood disruption through time-variant topological analysis,(29)for delay propagation under extreme rainfall with multiple impact factors,(44)for congestion and accessibility loss in agent-based simulations,(45)and for transportation system failure in urban flooding.(46)

Two studies approached the same question from network science. The first established that cities with efficient road networks can be less resilient than inefficient ones, because optimization for normal conditions removes the redundancy that absorbs disruption.(47)

The second showed that interdependent urban transport networks lose resilience faster when floods are compounded by targeted attacks on critical links.(48)

Together these studies explain why performance loss is not proportional to the number of closed links but depends on where the closure falls and on the redundancy of the surrounding network.

The two traditions also converge on a common implication. The San Francisco analysis locates the largest losses where flooded roads cut off employees from workplaces, and the network science analysis locates them where critical links concentrate flows.(42,47)

Both imply that a small number of links carry most of the systemic consequence, so a resilience strategy can be efficient if it targets those links rather than the network as a whole.

The studies also differ in how they separate direct and indirect consequences. Direct damage falls on the closed asset, whereas indirect consequences appear as rerouting, delay and foregone trips across the rest of the network. Most traffic studies measure the indirect side, and most asset studies measure the direct side, so the two literatures describe complementary halves of the same event.(37,42)

A complete account of a flood disruption would need both, but few studies in the corpus combine them.

The remaining three studies of this axis examined public transport and low-income settings, where the vulnerability pattern differs from that of car-dominated networks.

Multi-modal public transport was analysed under rainstorm waterlogging disasters in China,(49)public transport vulnerability to urban flooding was mapped in a GIS framework that combines network risk with population exposure,(50)and flood-induced traffic disruption was assessed in Kampala's urban road system.(51)

Among these, the low-income cases stand out because data scarcity limits the resolution of the assessment rather than the severity of the exposure.

Public transport networks differ from road networks in two respects that change the vulnerability picture. Their services run on fixed routes, so a closure cannot be bypassed by arbitrary rerouting, and their users are disproportionately people without a car, for whom the closure is absolute rather than a matter of delay.(49,50)

The corpus reflects this: the public transport studies report accessibility loss more than delay, whereas the road studies report the reverse.

The axis shares one methodological weakness. Most of the traffic models are calibrated rather than validated against observed disruptions, so the magnitude of delay and accessibility loss is sensitive to the baseline congestion and to assumptions about rerouting behaviour. This limits the transfer of quantitative results between cities.

Recovery, restoration and adaptation

Twelve studies addressed recovery, restoration or adaptation, and this axis shows the least methodological consensus. Three studies developed restoration models. Bridge restoration is the most formalized component, with models that quantify flood resilience from restoration curves(18) and metrics that connect sustainability and climate resilience to asset recovery.(32)

Flood recovery strategies were also optimized for road network disruptions in Shenzhen from isochrone analysis, treating the time needed to restore reachable areas as the recovery target.(52)

Recovery is measured in three ways across the axis: as the time to restore a component, as the shape of the restoration curve, and as the speed with which accessibility returns to its pre-disruption level.(18,52)

The three are not interchangeable, because a component restored early can remain unreachable if the surrounding network is still closed. This explains why rapidity, the recovery analogue of robustness, has no agreed definition, and why recovery findings are harder to compare than vulnerability findings.(32)

Four studies framed adaptation as the complement of restoration. The restoration-adaptation problem was modelled jointly for multimodal networks to move them from flood-prone to flood-ready states, treating multimodality and traveller uncertainty as the two main difficulties.(53)

Adaptive capacity was proposed as a distinct determinant of resilience to extreme floods, beyond the static properties of the network.(19)

Adaptation investments for transport resilience were reviewed with recommendations for prioritizing them across uneven national risks.(54)Enhancement strategies were assessed for urban transportation infrastructure coping with extreme rainfall.(55)

Adaptation and recovery are distinguished in the corpus by their timing. Recovery operates after a disruption and seeks to restore service, whereas adaptation operates before and seeks to reduce the susceptibility of the network to the next event. The two are linked, because the way a network is restored shapes its future exposure, a connection made explicit by the restoration-adaptation modelling of multimodal systems.(53)

Pre-event investment and post-event repair are therefore competing uses of the same budget, and few studies in the axis evaluate the trade-off explicitly.(54)

Three studies incorporated equity or capability considerations. A capability approach measured flood impacts on transport network resilience in Ennis, Ireland, treating mobility loss as a reduction of the functionings people can achieve.(33)

Human capabilities were integrated into flood vulnerability assessments for transport systems.(56)

Equity was included in resilient transport network planning from a flood impact perspective.(57)

The remaining studies examined compound failure scenarios for public transport,(58)scour maintenance strategies for aging bridges in flood-prone zones with distributional implications,(59) and resilient transport design to reduce flood vulnerability in the emerging-coastal city of Ho Chi Minh.(60)

The axis leaves two questions open. Recovery speed is measured at component level in most studies of the axis rather than at network level, so rapidity lacks a common definition across studies. The effectiveness of adaptation strategies is asserted in most cases but evaluated against outcomes in few, which weakens the evidence for any specific investment.

Across the five axes, two patterns recur. The first is a gradient of maturity, from concepts and vulnerability metrics, which are well established, to recovery, which is still emerging. The second is a persistent gap between the asset view and the user view, which no single metric family bridges completely. Both patterns frame the discussion that follows.

A third recurring pattern is geographic: most findings come from European, East Asian and North American networks, and the behaviour of networks in lower-income and coastal megacities is inferred more than observed.(51,60)

DISCUSSION

The principal finding of this synthesis is that transport network resilience to climate shocks is measured with a mature set of topological and performance metrics but a still immature set of recovery metrics, and that the choice of metric, hazard representation and scale determines what a study concludes about vulnerability. This pattern is not an artefact of the selection, because the same diagnosis appears in the most recent systematic reviews of the field.(9,11)

Level of evidence and consistency

Consistency is highest in the conceptual and metrics axes, where independent reviews arrive at the same classification of measures.(11,31)

The convergence between the efficiency-resilience trade-off reported in network science(47) and the empirical congestion results(42)is notable, because the two traditions use different data and yet agree that networks optimized for normal conditions lose more performance under shock. The bridge literature reinforces the point from the asset side, describing how loss of one structure cascades through connected systems.(5,61)

The level of evidence is uneven across axes in a way that matters for confidence. Conceptual claims rest on consensus among reviews, which is strong but indirect, while metric claims rest on case studies whose rankings depend on local data.(27,31)

Recovery claims are the weakest, because they rest on models that have not been confronted with observed recoveries. Confidence in a finding should therefore be read as highest for the classification of metrics, intermediate for exposure and performance loss, and lowest for recovery.

The evidence is thinner on recovery. Restoration models exist mainly for bridges,(18)and whole-network recovery is rarely propagated from component models, which explains why rapidity is

measured inconsistently across studies.(9,12)

The maritime and shipping literature reproduces the same imbalance, treating network resilience in detail but climate-driven recovery only partially.(13,14)

Underground transport space adds a further gap, because flood resilience there is reviewed as current status rather than as quantified recovery.(6)

Divergences concentrate on what the metric should capture. Topological indices rank links without travel demand, whereas accessibility measures incorporate destinations and population, and the two can disagree on which links are critical.(27,30)

This divergence is explained by measurement rather than by contradiction: topological measures describe the network, accessibility measures describe its users, and neither alone captures both.(7,16)

A second divergence concerns hazard detail. Studies that represent partial closure through depth-disruption functions report smaller but more widely distributed losses than binary closure models,(34)which matters for prioritization because the two approaches identify different critical assets.

A third divergence is spatial: national and city-level analyses attribute vulnerability to different determinants, since urban form and administrative boundaries shape the result.(22,23,26)

Applicability varies by mode and region. The road literature is the largest and most methodologically developed, followed by rail and public transport, while maritime and freight networks are treated separately and rarely integrated with land networks.(10,13)

Regional coverage is equally uneven: high-income cities supply most validated traffic models, whereas low-income settings appear mainly through coarser GIS assessments whose data constraints limit comparability.(50,51)

Consistency also extends to the exposure estimates. The global multi-hazard analysis and the European road assessment measure exposure at different scales, yet both conclude that flood exposure is concentrated and that a modest share of assets drives most of the risk.(2,4)

Agreement at the aggregate level does not resolve local ranking, because the critical asset at continental scale is not necessarily the critical asset for a single city. This scale dependence recurs throughout the corpus and is best treated as a property of the problem rather than as a defect of any one study.

Comparison with previous reviews supports the synthesis. The conceptual discussion by Mattsson and Jenelius already warned that vulnerability and resilience require different measures, and the present corpus confirms that warning empirically.(7)

The comprehensive review of disaster performance measures identified the same gap between pre-event and post-event metrics that this review finds a decade later.(9)

Infrastructure-level reviews reach the same conclusion for non-transport sectors, which suggests the problem is general to critical infrastructure rather than specific to transport.(12,62)

Game-theoretic treatments add that strategic interaction between network users and defenders changes vulnerability, a dimension absent from most of the metric literature.(15)

Implications for policy and practice

For practice, the synthesis supports accessibility-based and hybrid metrics as the most decision-relevant, because they connect network failure to the populations and destinations affected.(30,32)

The global and continental exposure estimates indicate that adaptation cannot be uniform: priorities must follow the concentration of exposed assets and the recurrence of the hazard.(2,4)

The cascade results argue for protecting the few links whose failure severs a corridor, as the Dawlish case illustrates.(40,41)

Recovery planning should borrow the formalized restoration models developed for bridges and extend them to whole networks, and should make distributional criteria explicit rather than implicit.(18,57)

The linked treatment of resilience, vulnerability and adaptation described for metropolitan spaces suggests that policy should treat these three as a single design problem rather than as separate agendas.(63)

The efficiency-resilience trade-off has a concrete policy meaning. Measures that reduce travel time in normal conditions, such as concentrating flows on a few fast corridors, can raise the cost of a climate shock by removing alternatives.(47)

Policy that treats redundancy as wasted capacity will therefore underinvest in resilience. The same logic applies to maintenance: deferring scour protection on a low-traffic bridge is efficient

until the bridge fails, at which point the indirect cost far exceeds the saving.(5,59)

Putting these findings into practice requires data that are currently scarce. Validated metrics of recovery need observations of network performance before, during and after a disruption, and such series exist for only a few cities and events.(28,42)

Open disruption datasets would allow the field to move from calibration to validation, and would let low-income cities benchmark their networks against better-documented systems rather than against assumptions.(51)

Standardized vulnerability and recovery metrics should be adopted so that studies across cities and hazards can be compared, building on the classifications already available.(11,31)

Dynamic and multi-hazard assessments should be validated against observed disruptions, which requires open datasets of network performance during floods and storms.(28,42)

Distributional criteria should be embedded in recovery and adaptation planning so that equity is measured rather than assumed.(33,57)

A fourth need follows from the mode and region gaps. Maritime, rail and public transport resilience should be connected to the road-based methods that dominate the field, so that a city or corridor can be assessed as one coupled system rather than as separate networks.(13,24)

CONCLUSIONS

The review characterized transport network resilience and vulnerability as complementary but non-standardized properties whose measurement spans topological, performance and accessibility families. It described the vulnerability metrics applied in the field and their relative strengths, with hybrid and accessibility measures emerging as the most informative. It established that flooding dominates hazard representation through depth-disruption functions and that multi-hazard exposure is global and uneven.

It synthesized the evidence that climate shocks propagate as congestion and accessibility loss and that efficiency can trade off with resilience. It showed that recovery is the least standardized dimension, that bridge restoration is its most formalized component and that equity considerations are only beginning to enter adaptation planning.

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