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Resilient Transportation Investment Under Constrained Budgets

A Framework for Prioritizing Vulnerable Corridors

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Abstract:
Climate change is increasing the probability that transportation corridors will be disrupted by flooding, landslides, extreme heat, wildfire, coastal hazards, and compound events. Yet the agencies responsible for roads, bridges, transit routes, and freight connections rarely possess sufficient capital to eliminate every vulnerability. This article develops a Resilient Corridor Investment Prioritization (RCIP) framework for selecting investments under constrained budgets. The framework integrates hazard exposure, asset condition, network criticality, consequences for essential access, distributional equity, lifecycle value, implementation readiness, and adaptive flexibility. It combines transparent multicriteria assessment with scenario testing, minimum equity and safety thresholds, and portfolio sequencing across low-, moderate-, and high-investment interventions. Illustrative applications in King County, Washington; metropolitan Mumbai, India; and Rotterdam-Rijnmond, the Netherlands, demonstrate how the same decision logic can operate across different governance, climatic, and fiscal contexts. The comparison shows that vulnerability alone is an inadequate basis for capital programming. Corridors become priorities when physical susceptibility intersects with limited redundancy, high social consequence, and feasible interventions that remain useful under multiple futures. The article argues that resilience should be institutionalized as a recurring portfolio-management function linked to asset management, community knowledge, maintenance budgets, and explicit adaptation triggers. RCIP offers a replicable approach for directing scarce resources toward networks whose continued function matters most, while preserving the option to escalate investment as risks and fiscal capacity change.

Keywords: climate adaptation; transportation resilience; infrastructure prioritization; vulnerable corridors; multicriteria analysis; equity; asset management; adaptive pathways

1. Introduction

Transportation agencies face a widening mismatch between climate risk and fiscal capacity. Roads, bridges, railways, culverts, slopes, drainage systems, and transit facilities were commonly designed from historical observations that no longer represent the full range of plausible conditions. At the same time, deferred maintenance, construction-cost escalation, and competition among safety, mobility, state-of-good-repair, and decarbonization programs limit the resources available for adaptation. The resulting problem is not simply how to make infrastructure resilient. It is how to choose which corridors should be protected first, what level of intervention is proportionate, and how a defensible portfolio can be assembled when complete reconstruction is unaffordable.

Existing vulnerability assessments have substantially improved the identification of assets exposed to climate hazards. Exposure maps, fragility functions, network models, and social-vulnerability indices can reveal where disruption may occur and whom it may affect (Cutter et al., 2003; Koks et al., 2019; Pregnolato et al., 2017). However, capital programming requires a further decision. A highly exposed asset may have an accessible detour, serve relatively few essential trips, or be inexpensive to restore. A moderately exposed corridor may be the only route to a hospital, ferry terminal, industrial district, or rural community. The latter can warrant earlier action even if its physical hazard score is lower. Resilience prioritization therefore requires a shift from ranking vulnerable assets to evaluating the public consequences of network failure.

This article proposes the Resilient Corridor Investment Prioritization framework, hereafter RCIP, as a bridge between climate-risk assessment and constrained capital programming. RCIP is designed for corridor-level decisions rather than isolated asset rankings. It treats resilience as the capacity to maintain or rapidly restore socially necessary accessibility, not merely the capacity of an individual structure to resist damage. The framework also rejects the assumption that a single weighted score can substitute for deliberation. Quantitative scores are useful for consistency and screening, but they must be accompanied by equity floors, scenario sensitivity, portfolio constraints, and transparent documentation of value judgments.

Three research questions guide the analysis. First, which criteria are necessary to translate transportation vulnerability into an investment priority? Second, how can agencies combine those criteria without obscuring uncertainty or distributional consequences? Third, which institutional practices allow a prioritization framework to remain useful as hazards, asset condition, community needs, and budgets change? Comparative illustrations from King County, Mumbai, and Rotterdam-Rijnmond test the framework across a county road system, a rapidly growing coastal megacity, and a mature delta-management context.

2. From Vulnerability Assessment to Investment Choice

2.1 Resilience as networked accessibility

Transportation resilience is variously defined through robustness, redundancy, rapidity, and resourcefulness, but these attributes become meaningful only in relation to services that a network enables. A road remaining intact is of limited value if the bridge, power supply, drainage system, or connecting transit service on which it depends has failed. Conversely, a damaged asset need not cause a severe societal loss when substitute routes and modes preserve access. Performance should therefore be assessed at the corridor and network level, with attention to travel-time loss, isolation, freight disruption, emergency response, and access to employment, education, food, and health care (Faturechi & Miller-

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Hooks, 2015; Hallegatte et al., 2019). This service-based perspective also clarifies why redundancy is not a luxury. It is a form of risk reduction whose value rises when alternative paths are scarce.

2.2 The limits of benefit-cost analysis and rank ordering

Conventional benefit-cost analysis can compare monetized reductions in expected damage and delay, but it tends to privilege impacts that are readily priced and populations with high measured travel demand or income. It can undervalue the avoidance of community isolation, the reliability of paratransit, the continuity of subsistence travel, and the disproportionate burden of repeated disruption on households with little adaptive capacity. Multicriteria decision analysis broadens the decision space by making nonmarket objectives explicit, yet it can create false precision if scores and weights are treated as objective facts (Barfod & Salling, 2015). A corridor that ranks first under one weight set and ninth under another is not a stable priority. Robust prioritization must disclose such sensitivity and identify projects that perform acceptably across plausible assumptions.

2.3 Adaptive pathways and staged investment

Climate uncertainty does not justify inaction, nor does it require immediate construction to the most extreme design condition. Dynamic adaptive policy pathways distinguish near-term actions from future decisions triggered by observed change (Haasnoot et al., 2013). For transportation agencies, this can mean pairing drainage maintenance and monitoring with a culvert retrofit, reserving right of way for a later realignment, or strengthening a slope while establishing thresholds for relocation. Staging reduces near-term fiscal pressure and preserves flexibility, provided that early actions do not lock the agency into a failing pathway. Safe-to-fail measures, which limit consequences when protection is exceeded, can complement fail-safe engineering where complete resistance is technically or financially unrealistic (Ahern, 2011).

3. Methodology and Comparative Design

The article uses design-oriented comparative analysis. It synthesizes scholarship on transportation resilience, infrastructure prioritization, social vulnerability, and adaptive planning with guidance from the Federal Highway Administration, the World Bank, the Intergovernmental Panel on Climate Change, and the Dutch Delta Programme (Federal Highway Administration, 2017; Hallegatte et al., 2019; Intergovernmental Panel on Climate Change, 2022; Ministry of Infrastructure and Water Management et al., 2023). The resulting framework is examined through three illustrative cases selected for maximum institutional and geographic variation. The cases are not scored against one another, and the analysis does not claim to reproduce an agency capital program. Instead, each case demonstrates how the same decision rules alter the interpretation of vulnerability and feasible intervention.

King County represents a large county road and transit environment with coastal, riverine, landslide, wildfire, and extreme-precipitation risks. Its mix of urban, suburban, island, and rural communities makes redundancy and essential access particularly important. Mumbai represents a dense coastal megacity where extreme rainfall, tidal conditions, drainage constraints, informal settlement, and exceptionally high travel demand produce compound consequences. Rotterdam-Rijnmond represents an

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advanced flood-risk governance setting where national standards, regional water authorities, port functions, and adaptive delta planning are deeply institutionalized. Together, the cases illuminate the transferability and limits of a corridor-based framework.

4. The Resilient Corridor Investment Prioritization Framework

RCIP is organized as a five-stage process: screen corridors, characterize consequences, develop intervention packages, construct robust portfolios, and monitor adaptation triggers. The unit of analysis is a functionally coherent corridor, including its critical structures, slopes, drainage, transit operations, active-mode connections, utility interdependencies, and plausible detours. This boundary avoids the common error of prioritizing a culvert or bridge without considering whether the remainder of the route can deliver the intended service.

Table 1. RCIP evaluation dimensions and decision evidence

Dimension	Core question	Indicative evidence
Hazard and uncertainty	Which current, future, and compound hazards can interrupt the corridor?	Flood depth and duration; slope instability; heat; wildfire; sea-level and precipitation scenarios; confidence ranges.
Condition and fragility	How likely are corridor components to fail or lose capacity?	Inspection ratings; drainage performance; maintenance history; material thresholds; failure modes; interdependencies.
Criticality and redundancy	What network function is lost, and are usable substitutes available?	Detour time and capacity; transit and freight role; daily and peak demand; bridge and ferry connections; modal alternatives.
Essential-access consequence	Which socially necessary trips are disrupted?	Access to hospitals, schools, shelters, food, emergency response, employment centers, and evacuation routes.
Equity and adaptive capacity	Who bears disruption and who can absorb it?	Income, disability, age, vehicle access, language, displacement risk, tribal and community knowledge, past underinvestment.
Lifecycle value	Which package reduces total risk at acceptable long-term cost?	Capital, maintenance, user delay, avoided damage, residual risk, co-benefits, funding eligibility, uncertainty ranges.
Readiness and	Can action begin, and can it adapt without lock-in?	Design maturity; permits; land; partnerships; near-term maintenance opportunities; scalability;

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flexibility		monitoring triggers.

Note. The dimensions should be documented separately before aggregation. Evidence may be quantitative, qualitative, or community-derived, but its source, scale, and uncertainty should be explicit.

4.1 Stage 1: Screen for material vulnerability

Screening begins with an inclusive inventory rather than a shortlist of politically prominent projects. Agencies overlay hazards with corridor assets and operations, then flag locations where exposure intersects with fragility or repeated disruption. Screening thresholds should be broad enough to capture low-probability, high-consequence events and compound hazards. Historical closures remain important but cannot define the future risk envelope. The output is a manageable set of corridors for deeper analysis, not a final ranking.

4.2 Stage 2: Evaluate consequences and equity

The second stage models the consequences of partial and complete loss under several durations. Network analysis estimates detour time, capacity loss, and isolation. Service mapping identifies effects on emergency response, transit, freight, schools, health care, and evacuation. Distributional analysis then asks whether disruption falls on communities with fewer substitutes, lower household resources, disability-related mobility needs, or a history of underinvestment. Equity operates as both a criterion and a constraint. A portfolio should meet a minimum share of benefits for priority populations, and no project should advance by shifting uncompensated risk onto them.

4.3 Stage 3: Develop intervention packages

Each corridor receives at least three intervention packages. A low-investment package emphasizes maintenance, operations, monitoring, warning, vegetation management, drainage cleaning, emergency contracts, and temporary redundancy. A moderate package may enlarge culverts, stabilize slopes, elevate electrical systems, add flood barriers, harden pavement, or create a secondary connection. A high-investment package may replace a bridge, elevate or realign a roadway, reconstruct drainage, relocate a facility, or redesign the corridor as multifunctional protective infrastructure. Packages should report residual risk and service performance, not merely construction scope.

4.4 Stage 4: Assemble robust portfolios

A transparent weighted sum can serve as a diagnostic, with normalized criterion scores multiplied by publicly reviewed weights. RCIP does not treat that result as the decision. Analysts vary weights, climate scenarios, closure durations, discount assumptions, and cost estimates. Projects that remain valuable across most combinations are robust priorities. Dominated alternatives, which cost more and perform worse across the relevant objectives, can be removed. Portfolio construction then applies budget ceilings, geographic balance, delivery capacity, equity floors, and dependencies among projects. This process frequently favors a mix of maintenance, targeted retrofits, redundancy, and a small number of transformative projects over a portfolio consisting only of the highest-cost reconstructions.

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4.5 Stage 5: Monitor triggers and revise

The portfolio becomes an adaptive program when each staged investment has observable triggers. Examples include a threshold number of closures, measured settlement, rising maintenance cost, a change in flood recurrence, loss of detour capacity, or development that increases essential demand. Annual asset management can update condition and readiness, while climate scenarios and community priorities can be reviewed at longer intervals. Public reporting should preserve previous scores and explanations so that changes in priority are traceable rather than appearing arbitrary.

Table 2. Investment tiers within an adaptive corridor portfolio

Tier	Typical measures	Selection logic	Trigger for escalation
Low investment	Maintenance, inspection, sensors, warning, emergency plans, spare parts, temporary transit or access provisions.	Immediate risk reduction; high readiness; protects service while larger options are evaluated.	Closures, deterioration, or hazard indicators exceed an agreed operational threshold.
Moderate investment	Culvert and drainage retrofit, slope stabilization, component elevation, heat-resistant materials, localized redundancy.	Addresses a defined failure mode with favorable lifecycle value and limited lock-in.	Residual risk, demand, or compound-event evidence makes localized protection insufficient.
High investment	Bridge replacement, corridor elevation or realignment, major drainage reconstruction, new redundant link, managed relocation.	Reserved for irreplaceable functions, intolerable consequences, or cases where incremental action is no longer viable.	Project is initiated when pathway trigger, funding window, or coordinated renewal point is reached.

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5. Illustrative Applications

5.1 King County, Washington: redundancy across diverse geographies

King County's 2025 Strategic Climate Action Plan identifies reliable and future-ready infrastructure as a flagship outcome and links resilience with equitable access to essential services (King County, 2025). A corridor lens is especially appropriate because county roads connect unincorporated communities across river valleys, steep terrain, forested areas, and islands. Flooding, landslides, wildfire, extreme heat, and coastal processes can affect both the primary route and its detour. The same closure can therefore produce very different consequences depending on network location.

Consider three archetypal corridors. A river-valley road may experience recurrent inundation and culvert stress but retain a reasonably short detour. An island arterial may have moderate physical exposure yet serve as the only continuous route between neighborhoods, ferry access, and emergency facilities. A foothill corridor may combine landslide and wildfire exposure with long detours and limited cellular coverage. A vulnerability-only ranking might prioritize the most frequently flooded site. RCIP can elevate the island or foothill route when redundancy, emergency access, and household adaptive capacity make failure more consequential.

The framework also changes the project response. For the river-valley corridor, drainage maintenance, flood-depth monitoring, detour management, and targeted culvert enlargement may outperform immediate realignment. For the island corridor, protecting several weak links and formalizing emergency transit or ferry contingencies can provide more service reliability than hardening one structure. For the foothill corridor, slope monitoring, vegetation management, emergency communications, and selective stabilization may precede a longer-term alternate alignment. These packages align resilience with asset management instead of treating adaptation as a separate funding category.

Equity requires more than mapping census indicators. Community engagement can reveal dialysis trips, school-bus dependence, tribal access, informal mutual-aid routes, and the needs of people who cannot drive. King County's climate-equity governance provides a basis for such knowledge to influence priorities, although RCIP would require that influence to be documented at corridor level rather than confined to countywide goals (King County, 2025).

5.2 Metropolitan Mumbai: compound flooding and unequal mobility

Mumbai's transportation system carries extraordinary passenger and freight demand through a low-lying coastal landscape. Extreme rainfall can coincide with high tides and constrained drainage, while dense development and informal settlement increase both exposure and the consequences of interruption. The Mumbai Climate Action Plan identifies urban flooding, water-resource management, and sustainable mobility as linked action areas and emphasizes the need for inclusive resilience (Municipal Corporation of Greater Mumbai, 2022). In this context, a corridor cannot be represented by roadway pavement alone. Suburban rail, metro, bus, walking access, stormwater drainage, utilities, and adjacent land uses form a single service system.

A demand-based ranking could direct investment toward the busiest central corridors, while an asset-based ranking could favor locations with the deepest modeled flooding. RCIP adds two correctives. First, it evaluates whether disruption removes access for communities with few modal or residential alternatives. Second, it recognizes that small neighborhood links can determine whether passengers reach a functioning high-capacity rail line. Station access roads, footpaths, drainage outfalls, and bus approaches may therefore generate large accessibility benefits despite carrying less vehicular traffic than a regional arterial.

Intervention packages should integrate gray, green, and operational measures. Drainage rehabilitation and pumping can be paired with permeable surfaces, retention space, elevated electrical equipment, redesigned station entrances, bus-priority continuity, and safe pedestrian routes. Where protection standards are exceeded, preplanned service substitution and real-time information reduce the social cost of failure. High-cost elevation or reconstruction should be reserved for corridors whose essential function cannot be maintained through distributed measures. This portfolio logic is particularly important in Mumbai because extensive needs make universal hardening fiscally impossible and because construction itself can disrupt livelihoods.

The equity floor is indispensable. Informal workers, low-income households, women making chained care trips, older adults, and people with disabilities may experience a one-hour disruption as a lost wage, missed treatment, or unsafe overnight journey. Engagement and disaggregated accessibility analysis should therefore complement travel-time and damage estimates. Projects that protect high-value property while worsening water displacement or access in adjacent settlements should fail the no-harm constraint even when their aggregate benefit-cost ratio is positive.

5.3 Rotterdam-Rijnmond: institutionalizing adaptive pathways

Rotterdam-Rijnmond combines globally significant port and logistics functions with dense urban districts, low-lying protected areas, and unembanked waterfronts. Dutch flood governance is distinguished by statutory standards, dedicated water institutions, periodic Delta Programme updates, and explicit attention to spatial adaptation. The Delta Programme seeks flood safety, freshwater security, and climate-resilient, water-robust spatial development, while adaptation strategies for the Port of Rotterdam integrate prevention, spatial measures, and crisis management (European Environment Agency, 2021; Ministry of Infrastructure and Water Management et al., 2023).

This mature setting demonstrates that prioritization does not disappear when institutional capacity is strong. It becomes more explicit about system dependencies and timing. Port roads, rail links, tunnels, movable barriers, utilities, and industrial sites must continue to function as an interdependent network. A corridor with strong direct protection can remain vulnerable if workers cannot reach it, power fails, or an inland connection floods. RCIP’s consequence and interdependency dimensions therefore prevent investment from concentrating only on the most visible protective structure.

Rotterdam also illustrates the value of adaptation pathways. Near-term spatial measures and crisis planning can preserve options while sea-level and river-discharge evidence is monitored. Major barriers, elevations, or relocations can be tied to decision points rather than predicted dates alone. Yet the Dutch case cautions against assuming that technical maturity guarantees distributive fairness. Investments that secure high-value port and waterfront functions may influence land values and transfer residual risk. Equity review, public explanation of acceptable residual risk, and attention to workers and unembanked communities remain necessary.

6. Comparative Findings

6.1 Criticality is relational, not intrinsic

Across the three cases, corridor criticality depends on the surrounding network and population. Traffic volume is informative but incomplete. A lightly traveled rural or island road can be more critical than an urban arterial when it has no substitute. A neighborhood access route can determine whether Mumbai's regional rail capacity remains usable. A Rotterdam freight link can be resilient only if employee access, power, and inland logistics remain functional. Agencies should therefore publish the indicators used to define criticality and test whether the same corridor remains important under partial failure and changing demand.

6.2 Equity changes both ranking and design

Equity is not adequately represented by adding a social-vulnerability score to an otherwise unchanged model. It changes the unit of benefit, the acceptable level of residual risk, the selection of intervention, and the engagement process. An equitable portfolio values continuity for people without vehicles, recognizes repeated small disruptions, prevents risk transfer, and reserves resources for historically underinvested communities. It also distinguishes equal geographic distribution from equitable allocation. Spending the same amount in every district can reproduce unequal protection when exposure, redundancy, and adaptive capacity differ.

6.3 Maintenance is a resilience investment

All three contexts reveal the importance of maintenance, although its institutional status varies. Cleared drainage, functioning pumps, inspected slopes, preserved pavement, maintained vegetation, operable barriers, and stocked replacement components can prevent or shorten failure. Capital programs often discount these actions because they are less visible and are funded from separate accounts. RCIP evaluates maintenance and operations alongside capital packages, allowing agencies to identify where modest recurring expenditure produces greater service reliability than a premature megaproject.

6.4 Robust portfolios outperform brittle rankings

A rank-ordered list implies that the first project should consume resources until completed, followed by the second. This logic can produce geographically concentrated, slow-delivery portfolios and defer inexpensive actions elsewhere. A robust portfolio instead asks which combination meets safety and equity thresholds, preserves essential access, fits delivery capacity, and performs across scenarios. It can include immediate maintenance on many corridors, moderate retrofits on several, design work for future high-cost projects, and one transformative investment. The portfolio is judged by system performance rather than the sum of project scores.

7. Implementation Guidance

Agencies can implement RCIP without waiting for a perfect regional model. The first cycle can use existing hazard layers, condition records, closure histories, route and facility data, and structured community workshops. Evidence quality should be graded, and missing information should reduce confidence rather than automatically reduce priority. The most consequential data gaps can then guide monitoring and analysis. Over time, the framework should be integrated with transportation asset management, capital improvement programming, hazard mitigation planning, and climate action reporting.

Governance should separate technical assessment from value-setting while connecting both transparently. Analysts can normalize evidence and test scenarios, but elected officials, agency leaders, affected communities, emergency managers, operators, and freight stakeholders must deliberate over weights, thresholds, and acceptable residual risk. The record should identify where priorities changed because of community knowledge or policy judgment. This transparency is more credible than presenting a composite score as if it were a scientific fact.

Fiscal strategy should match the intervention ladder. Operating funds support inspection and maintenance; resilience, hazard-mitigation, and transportation grants can finance targeted retrofits; bond programs and coordinated renewal can support major reconstruction. Projects should be designed to capture multiple benefits, including safety, emissions reduction, habitat, public space, and state of good repair, without allowing co-benefits to conceal the primary service objective. Lifecycle analysis should include maintenance obligations so that new protective assets do not create unfunded future liabilities.

Performance reporting should focus on service outcomes. Useful measures include population and essential facilities protected, reduction in expected isolation hours, detour availability, time to restore minimum service, share of benefits reaching priority populations, residual risk, and the proportion of corridors with monitored triggers. Counting projects or dollars alone cannot establish whether the network is more resilient.

8. Limitations and Research Agenda

RCIP is a decision framework rather than a predictive model, and its quality depends on the evidence and participation supporting it. Network models can understate informal travel, pedestrian access, and institutional interdependencies. Social-vulnerability indices can essentialize communities or obscure variation within geographic units. Monetized estimates remain uncertain, particularly for cascading disruption and long-duration recovery. The framework addresses these limitations through separate criterion reporting, uncertainty ranges, community knowledge, and sensitivity testing, but it cannot eliminate political conflict over acceptable risk.

Future research should test RCIP with observed closure and recovery data, compare portfolio outcomes with conventional benefit-cost and asset-condition rankings, and examine whether equity floors alter actual capital allocations. Methods are also needed to represent compound hazards, cross-agency dependencies, and induced land-use change more consistently. Longitudinal studies could evaluate whether adaptive triggers are acted upon or become symbolic. Finally, comparative work should

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investigate how agencies with limited analytical capacity can use simplified versions without losing transparency and distributive accountability.

9. Conclusion

Constrained budgets make prioritization unavoidable. The central question is whether scarcity will be managed through inherited project lists and visible failures or through a transparent assessment of which transportation services society cannot afford to lose. The RCIP framework advances the latter approach. It links hazards and asset fragility to network criticality, essential access, equity, lifecycle value, delivery readiness, and adaptive flexibility. It then moves beyond a single ranking by testing sensitivity, enforcing minimum safeguards, and constructing a staged portfolio.

The cases of King County, Mumbai, and Rotterdam-Rijnmond demonstrate that the logic is transferable even when hazards, institutions, and resources differ. Each context benefits from treating corridors as interdependent service systems, valuing maintenance and redundancy, and reserving transformative construction for functions whose consequences justify it. Resilient transportation investment is therefore not synonymous with building the strongest infrastructure everywhere. It is the disciplined allocation of limited resources to preserve socially necessary accessibility, reduce unequal disruption, and retain credible pathways for stronger action as conditions change.

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