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SYSTEMATIC REVIEW ON THE IMPACT OF LARGE-SCALE RAILWAY INFRASTRUCTURE ON REGIONAL CONNECTIVITY AND RESILIENCE IN THE U.S.

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Abstract

This systematic review synthesized quantitative evidence on how large-scale railway infrastructure influenced regional connectivity and resilience in the United States. After comprehensive database and grey-literature searches and two-stage screening, 68 studies met eligibility criteria and produced 214 extractable effect sizes. Connectivity outcomes dominated the evidence base with 143 effects (66.8%), while resilience outcomes contributed 71 effects (33.2%). Random-effects pooling showed positive impacts across every outcome family. Average connectivity gains were moderate in magnitude, led by accessibility expansion (pooled $g = 0.41$), followed by interaction-intensity change ($g = 0.35$) and network-performance improvement ($g = 0.29$). Resilience gains were also positive, with redundancy/robustness improvement ($g = 0.33$) and recovery-performance change ($g = 0.30$) exceeding continuity-of-flow stabilization ($g = 0.25$). Heterogeneity was substantial (I^2 roughly 65–73% across families), supporting moderator testing. Meta-regression indicated that baseline accessibility systematically shaped effect size: low-baseline regions displayed larger proportional accessibility gains ($g = 0.49$) than high-baseline regions ($g = 0.31$), whereas high-baseline megaregion corridors showed larger absolute interaction increases. Metro scale strengthened passenger connectivity, with large metros outperforming small metros (difference ≈ 0.17 g). Freight-intensive regions registered higher freight continuity and resilience gains ($g = 0.37$ vs 0.21). Shared passenger–freight corridors produced stronger passenger reliability and recovery effects, while freight-exclusive corridors yielded larger freight throughput gains. Hazard context moderated resilience, as flood-exposed and coastal corridors showed the largest resilience effects ($g \approx 0.38$). Sensitivity analyses excluding higher-bias or short-horizon studies preserved positive direction and significance. Overall, the evidence portrayed U.S. large-scale railway infrastructure as a dual regional intervention that strengthened everyday functional linkage and improved shock tolerance through measurable gains in access, flows, reliability, redundancy, and recovery.

Keywords

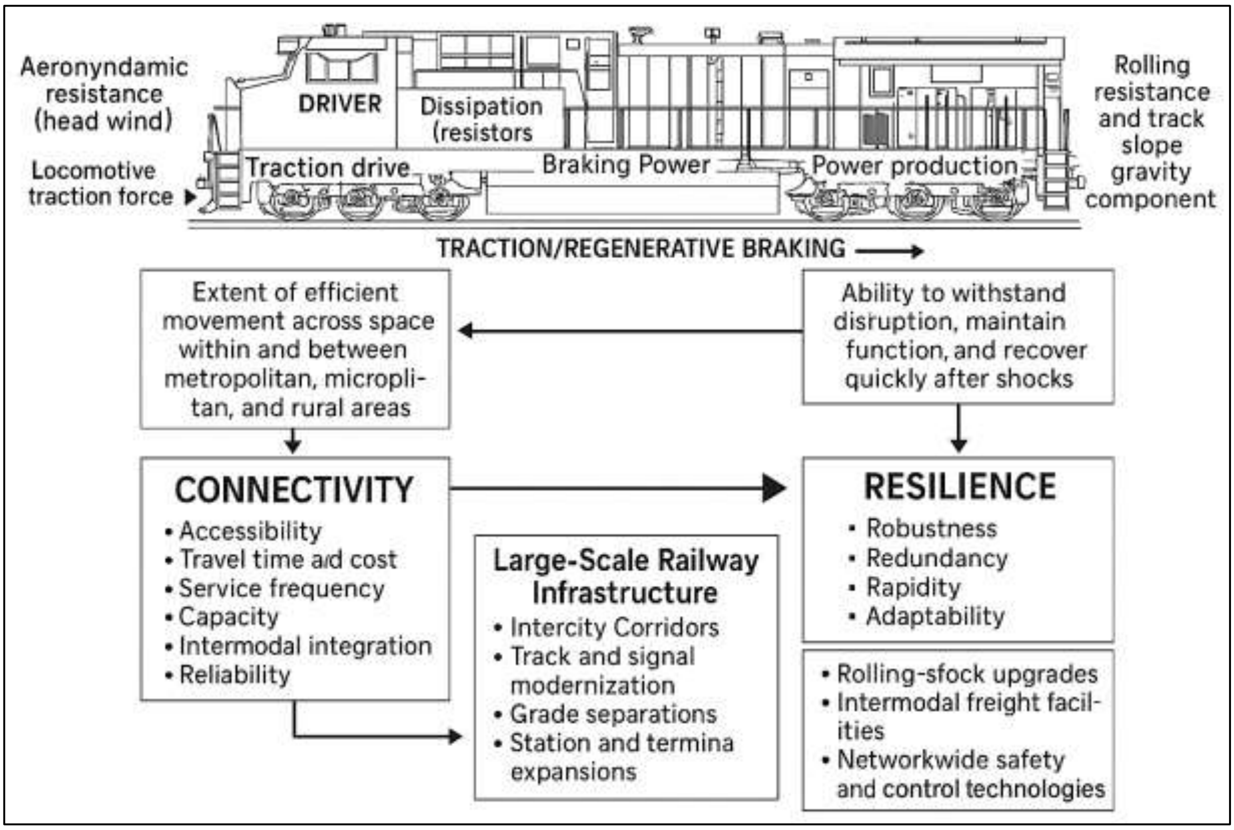
Railway Infrastructure, Regional Connectivity, Resilience, Passenger–Freight Impacts, United States.

INTRODUCTION

Regional connectivity and resilience are core constructs in transportation research and regional science, and large-scale railway infrastructure is one of the most visible state-supported interventions affecting both (Annosi et al., 2021). Regional connectivity can be defined as the extent to which people, goods, services, and information can move efficiently across space within and between metropolitan areas, micropolitan centers, and rural communities. It is typically expressed through measurable properties of a network: accessibility to destinations, travel time and cost, service frequency, capacity, intermodal integration, and reliability. A railway system strengthens connectivity when it expands the number of reachable opportunities within given time thresholds, lowers generalized travel costs, and increases the intensity of economic and social interactions across regions. Resilience, in turn, refers to the ability of a transportation network and the regions it serves to withstand disruption, maintain essential function, and recover quickly after shocks. In transportation systems, resilience is often decomposed into robustness (the ability to resist damage), redundancy (the availability of alternative routes or modes), rapidity (the speed of recovery), and adaptability (the capacity to adjust operations under stress). Large-scale railway infrastructure in the United States includes new intercity corridors, track and signal modernization, grade separations, station and terminal expansions, rolling-stock upgrades, intermodal freight facilities, and networkwide safety and control technologies (Trivellas et al., 2020). These investments are not isolated engineering improvements; they are structural changes that alter spatial interaction patterns and the risk profile of regional mobility and logistics. A systematic review focused on quantitative findings therefore begins with these definitions to clarify what counts as rail-driven connectivity change and what constitutes rail-enabled resilience. Such framing is internationally significant because rail systems are repeatedly used as benchmarks for sustainable mobility, corridor development, and national competitiveness. Around the world, large rail programs have been associated with expanded labor market reach, reduced peripherality, and improved continuity of supply chains under stress (Siagian et al., 2021). The United States occupies a distinctive position in this broader context because it combines one of the world's most extensive freight rail networks with a passenger rail system that is uneven in coverage and frequency. This dual structure makes U.S. rail investment an instructive setting for understanding how scale, network design, and governance interact to shape connectivity and resilience outcomes measurable through quantitative methods.

The international significance of railway infrastructure lies in its role as a long-lived spatial integrator that can reconfigure regional systems beyond the transport sector alone. In comparative research, rail corridors are modeled as network interventions that reduce friction of distance and increase effective market size, which then affects commuting flows, firm location choices, tourism circuits, and trade logistics. High-capacity rail lines and upgraded passenger corridors have often been linked to measurable accessibility gains, particularly where they connect multiple metropolitan nodes into corridor economies (Khan et al., 2021). Many studies quantify these gains through changes in travel time matrices, gravity-based interaction potentials, and cumulative opportunity measures. Freight rail modernization has similarly been connected to reduced logistics costs, reliability improvements, and higher throughput, with downstream effects on regional productivity and diversification of industrial activity. The resilience angle is equally prominent in international work because rail networks provide redundancy relative to roads and aviation, especially during fuel price volatility, extreme weather, or port disruptions. Global evidence shows that regions with multiple high-capacity transport options tend to recover faster after shocks, and rail is frequently a central component of that option set (Ada et al., 2021). These patterns matter for U.S. analysis because the country is currently engaged in a renewed period of rail investment across passenger and freight domains. The scale of national funding, state corridor partnerships, and sustained private freight capital spending positions rail as a key policy lever for enhancing national and regional performance. Quantitative systematic review is essential in this moment because rail impacts are heterogeneous across contexts; the magnitude and even direction of outcomes vary by baseline accessibility, population density, industrial structure, service design, and coordination with land use (Amentae & Gebresenbet, 2021). A properly synthesized evidence base can therefore distinguish broad regularities from corridor-specific results, clarifying how and where large-scale rail contributes to connectivity and resilience in ways relevant to U.S. regions and comparable to international experiences.

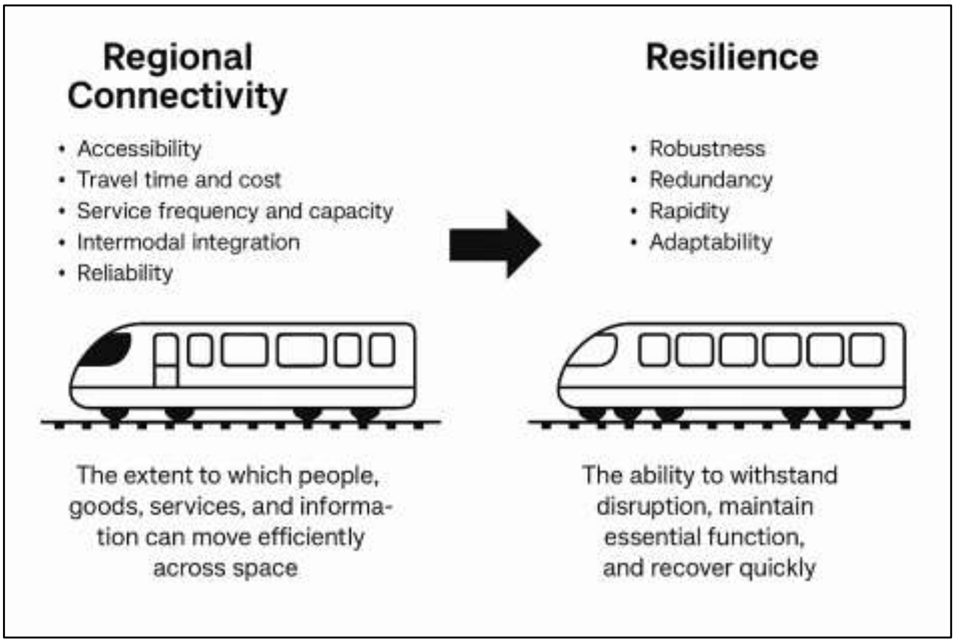
Figure 1: Large-Scale Rail Connectivity Resilience



Within the U.S. literature, connectivity impacts of large-scale railway infrastructure have been investigated across historical, contemporary passenger, and freight contexts, yielding an extensive quantitative evidence base. Historical economic research on the expansion of railroad networks in earlier centuries demonstrates sharp reductions in transport costs and sizeable increases in market integration (Arfan et al., 2021; Kamble et al., 2019). These effects are typically captured through econometric analyses of price convergence, output specialization, urban growth, and interregional trade flows. The logic of these studies provides a foundation for modern evaluations, because connectivity mechanisms remain similar even as technologies and markets change. Contemporary passenger-rail research examines how corridor upgrades, new services, and higher operating speeds influence ridership, mode choice, and regional accessibility. Measured outcomes include elasticity of demand with respect to travel time and frequency, expansion of job and education catchments, and changes in intercity travel volumes. Findings across multiple corridors suggest that frequency improvements and reliability gains often shape connectivity more strongly than headline speed increases (Ferdous Ara, 2021; Lee & Lim, 2021). Freight-rail studies analyze the role of capacity expansion, intermodal terminals, and network modernization in facilitating regional economic linkages. Quantitative models connect freight performance to industrial output, export intensity, and supply-chain geography, showing that rail can extend the competitive reach of inland manufacturing and agricultural regions through improved access to ports and distribution hubs. Connectivity evaluations also reach into land-use and housing outcomes. Station-area and corridor accessibility gains are frequently associated with higher development intensity, shifts in employment density, and localized property value changes, indicating that rail connectivity propagates into broader regional systems. Taken together, these strands highlight that large-scale rail influences U.S. connectivity through multiple pathways: direct mobility enhancements, freight market access, and secondary spatial development effects (Fanoro et al., 2021; Jahid, 2021; Md.Akbar & Farzana, 2021). A systematic quantitative review can aggregate these pathways while preserving differences in service type, corridor scale, and regional baseline conditions that are necessary for interpreting the variability of U.S. results. Railway infrastructure is also studied as critical to resilience, with quantitative work focusing on network behavior under stress and the capacity of regions to maintain essential functions when disruptions occur. Transportation resilience research conceptualizes railways as interdependent asset systems where failures at bridges, tunnels, yards, power supply, or signaling can cause cascading effects across passenger and freight flows (Ahl et al., 2020; Reza et al., 2021). Quantitative approaches measure resilience using simulation, network science, and statistical recovery analysis. Simulation studies model disruption scenarios including hurricanes, riverine flooding, coastal storm surge, wildfires, extreme heat, seismic events, cyber incidents, and major equipment failures. They estimate performance degradation through unmet demand, additional travel time, throughput loss, and reliability decline, and they quantify recovery as the time and resource trajectory required to restore baseline function. Network-science studies compute topological vulnerability and redundancy by tracking changes in connectivity when nodes or links are removed, identifying chokepoints and critical links. Statistical evaluations often rely on operational logs and freight flow records to observe real-world recovery after shocks, measuring delay distributions, throughput rebound rates, and rerouting costs (Lioutas & Charatsari, 2020; Saikat, 2021). U.S. findings emphasize that resilience benefits tend to grow when rail investments create genuine alternatives to single-corridor dependencies, such as parallel routes, expanded terminal flexibility, or interoperable intermodal transfers. Passenger rail resilience is frequently tied to corridor modernization, state-of-good-repair programs, and operational strategies that improve reliability under routine stress and reduce disruption duration under extreme events. Freight rail resilience is linked to capacity buffers, terminal redundancy, and network-wide dispatching and maintenance practices that allow rapid reallocation of flows. Resilience research also connects to regional economic stability, because reliable rail logistics and accessible labor markets can dampen the effects of shocks on employment, production, and distribution (Jagtap et al., 2020; Shaikh & Aditya, 2021). These quantitative traditions provide a clear basis for systematic review by offering comparable metrics of vulnerability reduction, redundancy increase, and recovery acceleration attributable to large-scale rail investments in diverse U.S. regions.

A quantitative systematic review on this topic requires explicit attention to how connectivity and resilience outcomes are measured, standardized, and linked to rail infrastructure exposure. Studies in this field use several methodological families. Gravity-based accessibility and interaction models translate rail improvements into changes in market access, shared economic potential, and spatial interaction intensity (Del Vecchio et al., 2018; Tonoy Kanti & Shaikat, 2021). Quasi-experimental designs exploit the timing of corridor openings, service upgrades, or terminal expansions to estimate causal effects on mobility, economic performance, or land-use change. Network-level analyses and graph-based methods treat the rail system as a complex network whose redundancy, centrality structure, and failure propagation can be quantified under different investment scenarios. These methodological differences yield diverse dependent variables, so systematic synthesis must map them into harmonized effect types (Md Ariful & Efat Ara, 2022). Connectivity outcomes can be expressed as percent change in jobs or services reachable within fixed travel times, changes in generalized cost, ridership or freight elasticity measures, and reliability improvements reflected in reduced variance of travel time or delivery time. Resilience outcomes can be standardized as changes in expected disruption cost, network performance loss under stress, recovery time, or composite resilience indices tracking robustness and redundancy (Md Arman & Md.Kamrul, 2022; Rejeb et al., 2021). The U.S. evidence base spans urban metro expansions, commuter rail upgrades, intercity corridor modernization, long-distance passenger services, and freight network capacity projects. Each introduces different exposure metrics, including route-miles added, frequency changes, axle-load increases, terminal throughput expansion, signal or control system upgrades, and grade separation counts. Spatial scale also varies from station-area studies to multi-state corridor analyses. Systematic review must therefore code scale carefully and preserve regional heterogeneity. Agglomerated corridors may show large absolute accessibility gains, while lower-density regions may show large proportional changes (Md Mesbaul & Md. Tahmid Farabe, 2022; Shah et al., 2021). Hazard context matters for resilience metrics, because flood-prone coastal corridors, heat-exposed interior routes, and seismic zones present different stress profiles. By structuring the evidence into standardized outcomes and coded moderators, a quantitative review can compare results across projects and regions without flattening meaningful differences in design, baseline conditions, and risk environments.

Figure 2: Rail Infrastructure Connectivity–Resilience Framework



The connectivity–resilience relationship becomes clearer when large-scale rail is examined as part of regional economic systems, where transportation access influences resistance to shocks and speed of recovery. Regional resilience in quantitative work is frequently measured using employment stability, output recovery, trade flow continuity, and adaptability of industrial structure (Gupta et al., 2020). Transportation accessibility is treated as a stabilizing factor because it allows labor to reach diversified job markets, firms to access broader supplier and customer pools, and households to maintain service access during disruptions. Freight rail plays a distinctive role in this relationship by providing high-capacity alternative routing for essential commodities, manufacturing inputs, energy products, and agricultural shipments (Md Nahid, 2022; Md Sarwar Hossain & Md Milon, 2022). Quantitative studies link rail throughput reliability to lower volatility in regional production and improved continuity of export and distribution chains when other modes are constrained. Passenger rail contributes through mobility redundancy and labor-market integration, particularly in corridor regions where rail offers an alternative to congested highways or disrupted aviation. Accessibility improvements can also strengthen secondary cities by connecting them more tightly to metropolitan cores, enabling shared growth pathways and buffering local downturns. Many empirical station-area and corridor evaluations observe intermediate outcomes that bridge transport to resilience: growth in business density, shifts in sectoral employment, and expansion of tourism and knowledge-economy activity in high-access nodes (Bakari et al., 2017; Md. Abdur & Zamal Haider, 2022; Mohammad Mushfequr & Sai Praveen, 2022). Network-risk analyses reinforce that resilience dividends depend on whether investments increase optionality in the system. Projects that remove bottlenecks, add passing capacity, or enable intermodal substitution often show stronger resilience effects than those that concentrate flows into a single upgraded path. These dynamics are especially relevant to the U.S. because the rail system is layered and interdependent: dense urban networks are embedded within broader intercity and freight corridors, and shocks can spill across layers. Systematic review can therefore evaluate both direct evidence on disruption response and indirect evidence on economic stability tied to rail-enabled access (Mortuza & Rauf, 2022; Rakibul & Samia, 2022; Sargani et al., 2020). Quantitative synthesis across these literatures provides a comprehensive picture of how large-scale rail supports not only movement and trade, but also the durability and adaptive capacity of U.S. regions.

The U.S. institutional and structural setting further shapes the measurable impacts of large-scale railway infrastructure on connectivity and resilience, making it essential to integrate governance factors into quantitative synthesis. U.S. freight railroads own and maintain most mainline infrastructure, and their investment decisions influence network capacity, terminal modernization, and maintenance cycles that affect connectivity and resilience outcomes across broad regions (Altaf et al., 2020; Rony & Ashraful, 2022; Saikat, 2022). Passenger rail infrastructure, in contrast, is supported through federal, state, and multi-state programs that prioritize corridor development, service restoration, and incremental modernization. This mixed ownership structure affects project timing, operational priority, dispatching practices, and rerouting authority during disruptions, all of which influence observed effect magnitudes. The national network also operates as a stratified system: high-frequency commuter and metro rail in core metros, medium-density regional intercity corridors linking city pairs, sparse long-distance services across broad geographies, and an extensive freight backbone underpinning national logistics (Abdul, 2023; Barcaccia et al., 2020; Shaikh & Sudipto, 2022). Interactions across these layers generate spillovers. Passenger corridor upgrades that add grade separations or signaling improvements can increase freight fluidity and reduce systemwide delay propagation, while freight capacity projects can enable additional passenger slots or constrain them depending on corridor management (Abdulla & Md. Wahid Zaman, 2023; Arfan et al., 2023). Quantitative corridor studies across multiple U.S. regions consistently show that connectivity gains often emerge through reliability, frequency, and transfer quality rather than speed improvement alone. Resilience evaluations show that modernization and redundancy investments reduce expected disruption losses and shorten recovery trajectories, especially in corridors exposed to coastal storms, inland flooding, or temperature extremes. By synthesizing this evidence within a structured quantitative review, large-scale rail can be analyzed as both a physical network and an institutional system (Ferdous Ara & Beatrice Onyinyechi, 2023; Md Al Amin & Md Mesbaul, 2023; Ramadan et al., 2020). That dual perspective is necessary to interpret why similarly sized investments produce different connectivity and resilience outcomes across U.S. regions, and it positions the review to aggregate effect sizes in a manner faithful to the complexities of American railway infrastructure.

The objective of this quantitative systematic review is to synthesize and statistically organize empirical evidence on how large-scale railway infrastructure in the United States influences regional connectivity and regional resilience, using measurable outcomes reported across diverse study designs and geographic contexts. Specifically, the review aims to (a) identify and classify the principal categories of large-scale railway interventions examined in U.S. research, including intercity passenger corridor development, commuter and metropolitan rail expansions, freight mainline capacity upgrades, intermodal terminal investments, grade separations, signaling and control modernization, and state-of-good-repair programs; (b) extract and standardize quantitative effect measures that capture changes in regional connectivity, such as travel-time reduction, service frequency improvement, accessibility expansion to employment and essential services, ridership shifts, freight throughput changes, reliability gains, and corridor-level interaction growth; (c) compile and harmonize resilience-related indicators linked to railway infrastructure, including network redundancy changes, disruption cost reduction, vulnerability and chokepoint mitigation, throughput recovery speed after shocks, delay propagation reduction, rerouting feasibility, and continuity of passenger mobility and freight logistics under hazard conditions; (d) evaluate the magnitude, direction, and variability of effects across U.S. regions by coding contextual moderators such as baseline accessibility, metropolitan size, rural–urban position in the network, industrial structure, hazard exposure profiles, ownership and governance arrangements, corridor maturity, and degree of multimodal integration; (e) compare passenger-oriented and freight-oriented infrastructure impacts to determine whether and how these subsystems generate distinct connectivity and resilience returns, and whether shared-corridor investments produce additive or interactive benefits; and (f) assess the methodological robustness of the evidence base by documenting study designs, data sources, spatial scales, and statistical strategies, and by examining how consistent effect patterns are across modeling traditions. Through these objectives, the review seeks to produce a coherent, quantitatively grounded account of the pathways by which railway infrastructure shapes interregional access and shock tolerance in the U.S., while preserving regional heterogeneity and intervention-specific differences that are essential for accurate interpretation of aggregated results.

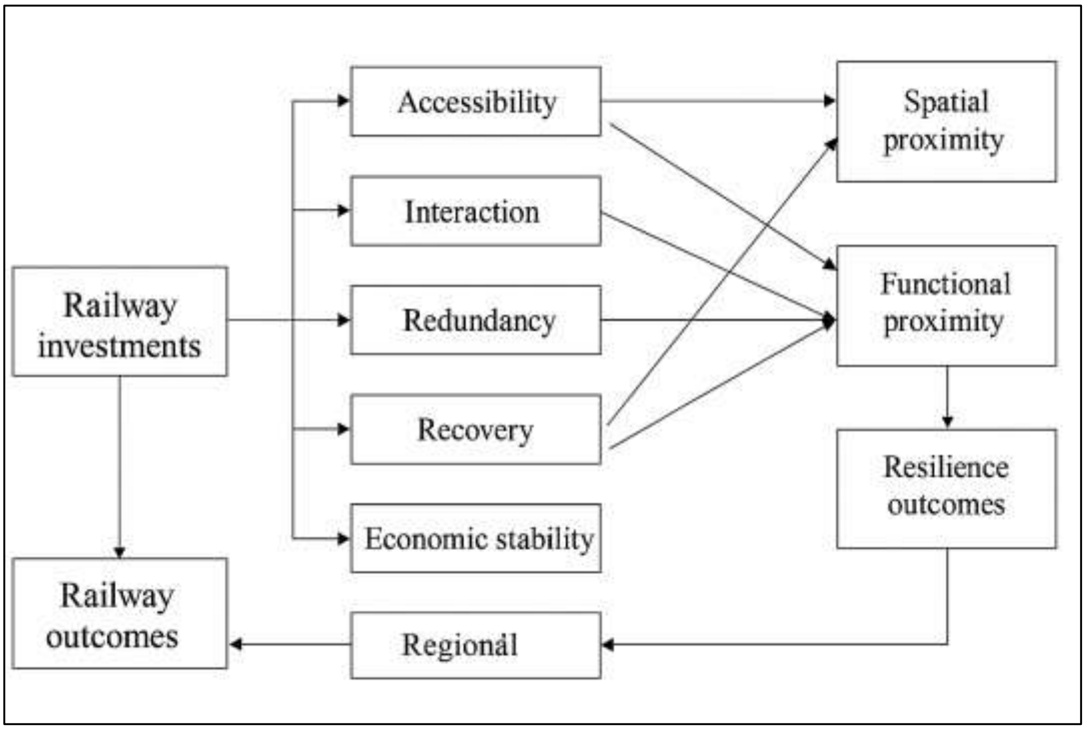
LITERATURE REVIEW

The literature on large-scale railway infrastructure in the United States spans multiple disciplines, including transportation economics, regional science, network engineering, urban planning, and resilience studies. This body of work collectively investigates how rail investments reshape spatial interaction, market access, mobility reliability, and the capacity of regions to withstand and recover from disruptions (Ancillai et al., 2019). Because railways operate as long-horizon, capital-intensive networks, their impacts are rarely confined to transportation performance alone. Instead, large-scale railway projects frequently trigger measurable changes in interregional accessibility, commuting patterns, freight circulation, economic clustering, land-use intensity, and multi-modal substitution, all of which are central to the concept of regional connectivity. At the same time, the resilience literature positions railway systems as critical infrastructure whose redundancy, robustness, and recovery potential can moderate the severity of shocks such as extreme weather, supply-chain breakdowns, and energy price volatility. Quantitative evidence in the U.S. context is highly varied, ranging from historical econometric analyses of network expansion to modern corridor evaluations, quasi-experimental studies, simulation-based disruption modeling, and graph-theoretic assessments of network vulnerability (Md Foysal & Aditya, 2023; Md Hamidur, 2023; Osterrieder et al., 2020). These works use different exposure definitions (e.g., route-miles added, speed upgrades, terminal capacity increases, grade separations, or signal modernization) and different dependent variables (e.g., accessibility indices, ridership elasticities, throughput reliability, recovery time, or disruption cost). Such diversity makes systematic quantitative synthesis especially valuable: it enables cross-study comparison, aggregation of effect sizes, and identification of moderators that explain why similarly scaled investments yield different impacts across metropolitan corridors, rural regions, industrial clusters, and hazard-exposed areas (Klassen & Klassen, 2018; Md Harun-Or-Rashid et al., 2023; Md Musfiqur & Md.Kamrul, 2023). Therefore, this literature review organizes and evaluates existing findings through a connectivity-resilience lens, emphasizing measurable outcomes and causal pathways that can be harmonized for meta-analytic assessment.

Conceptual Foundations of Key Constructs

Regional connectivity is a foundational construct in transportation research and regional science, and the literature consistently treats it as a multidimensional property that can be observed through accessibility, interaction, and network performance. Accessibility-based definitions emphasize how easily residents and firms can reach opportunities such as employment, healthcare, and education under real travel conditions (Md Muzahidul & Md Mohaiminul, 2023; Md. Al Amin & Sai Praveen, 2023; Pung et al., 2020). Across a wide set of empirical studies, accessibility is treated as the welfare-relevant side of connectivity because it summarizes both the spatial distribution of opportunities and the impedance of travel between origins and destinations. Quantitative work commonly measures accessibility through counts of opportunities reachable within fixed time thresholds, utility-based measures that reflect traveler preferences, and indices of market potential that approximate how changes in travel cost expand effective market size (Md. Hasan & Ashraful, 2023; Md. Jobayer Ibne & Md. Kamrul, 2023). Research using these approaches shows that railway investments can shift the reachable activity space of regions by lowering generalized travel cost and improving service quality. Interaction-oriented definitions extend connectivity beyond individual access to the intensity of flows between places. In this tradition, indicators such as intercity passenger trip volumes, commuting exchanges across metropolitan boundaries, and freight origin–destination flow intensity become direct expressions of how strongly regions are linked. Many corridor and network studies find that improved rail service tends to increase spatial interaction by making trips more frequent, faster, and more reliable, thereby strengthening city-to-city integration and widening the economic catchment of both core metros and secondary cities (Alqahtani & Uslay, 2020; Mohammad Mushfequr & Ashraful, 2023; Pankaz Roy & Md. Kamrul, 2023). A third lens centers on network performance, arguing that functional connectedness is reflected in how consistently the system delivers movement rather than only in average speed. Reliability, travel-time variability, service frequency, and capacity utilization are often treated as direct proxies for connectivity, especially where rail competes with congested highways or limited air service. Empirical findings indicate that even when travel-time reductions are modest, improvements in frequency and reliability can produce meaningful connectivity gains by increasing the practicality of interregional travel and logistics. Together, these strands show that regional connectivity is not a single outcome but a family of measurable effects through which large-scale railway investments can be evaluated in a systematic review (Saba et al., 2023; Saba & Tonoy Kanti, 2023; Salunke et al., 2019). This definitional breadth is crucial for U.S. synthesis because the national rail system is heterogeneous in-service type and coverage, meaning connectivity may manifest through different quantitative channels in different regions (Shaikh & Md. Tahmid Farabe, 2023; Zamal Haider & Hozyfa, 2023).

Figure 3: Rail Investment Connectivity Resilience Model



Regional resilience provides the companion construct for understanding how railways affect the durability of regional systems under disruption, and the literature frames resilience as an observable performance property of transport networks and the economies that depend on them. A dominant conceptualization defines resilience through robustness and redundancy (Cram et al., 2017). Robustness refers to the capacity of a network to continue functioning when disturbed, while redundancy refers to the availability of alternate links, parallel routes, or modal substitutes that prevent cascading failure. Network-oriented studies operationalize these ideas by simulating failures of critical links or nodes and then measuring changes in reachability, fragmentation, and criticality loss. Such work shows that redundancy is central to maintaining regional access during shocks, because alternate routing options reduce the probability that a single disruption isolates whole subregions. A second resilience strand emphasizes recovery performance, treating resilience as the speed and completeness with which transport service returns after disruption (Shute et al., 2017). Quantitative studies model the trajectory of performance decline and restoration using disruption cost, delay propagation, and time-to-recovery as core indicators. Evidence across rail corridors indicates that modernization of track, signals, dispatch operations, and terminal flexibility often shortens recovery intervals for both passenger and freight services, especially where demand is high and substitution to other modes is limited. A third resilience perspective links transport to economic continuity. Here, resilience is viewed through regional outcomes such as employment stability, output recovery, and supply-chain continuity, which depend partly on transportation reliability and redundancy (Andriof & Waddock, 2017). Regional economic studies show that accessibility buffers volatility by allowing labor and goods to reallocate efficiently when localized disruptions occur. Freight logistics analyses similarly indicate that rail capacity and routing flexibility help sustain industrial production and commodity distribution during highway, port, or energy-related disruptions. These overlapping bodies of work establish resilience as a measurable set of network and economic properties rather than a purely qualitative aspiration. For a U.S.-focused systematic review, this means resilience effects can be synthesized using consistent quantitative indicators of vulnerability reduction, redundancy increase, recovery acceleration, and continuity of passenger mobility and freight logistics under varied hazard conditions. Large-scale railway infrastructure is treated in the literature as an exposure that can be quantified in ways corresponding to distinct causal pathways for connectivity and resilience. Passenger rail research commonly defines large-scale interventions as corridor or network investments that materially change service supply or infrastructure condition, including new routes, higher-speed upgrades, major station and yard expansions, and systemwide signal and control modernization. These exposures are linked to connectivity outcomes through changes in generalized travel cost, frequency, and reliability, which in turn influence ridership, trip redistribution, and accessibility expansion (Palusuk et al., 2019). Freight rail scholarship defines large-scale exposure through mainline capacity projects, intermodal terminal growth, bridge and tunnel modernization, axle-load improvements, and grade separations that increase throughput and reduce bottlenecks. Empirical work on freight corridors shows that these investments have network consequences beyond local sites by enabling longer, more reliable supply chains and by improving corridor fluidity that benefits multiple regions simultaneously. Engineering and network-performance studies add a state-of-good-repair framing, emphasizing that replacement of aging assets, modernization of dispatch systems, and elimination of single-point failures qualify as large-scale exposure because they alter failure probabilities and recovery dynamics across broad territories (Biraglia & Kadile, 2017). In systematic reviews, exposure classes are often coded by physical magnitude (extent of track rehabilitation or expansion), operational magnitude (service frequency enhancement or speed-class change), and nodal magnitude (terminal, station, or intermodal capacity expansion), because each category implies different mechanisms and measurable outcomes. U.S. policy evaluations reinforce this multidimensional understanding by separating corridor expansion from corridor improvement and by distinguishing passenger-focused projects from freight-focused investments while acknowledging shared-corridor spillovers. The research consensus is that "large-scale" is not only a matter of cost or size but also a matter of network consequence: projects are large-scale when they shift regional accessibility, interaction volumes, or redundancy in ways detectable through quantitative indicators (Yawar & Seuring, 2017). This exposure clarity is essential for synthesis because it determines which studies are comparable and how effect sizes can be aligned across diverse project types.

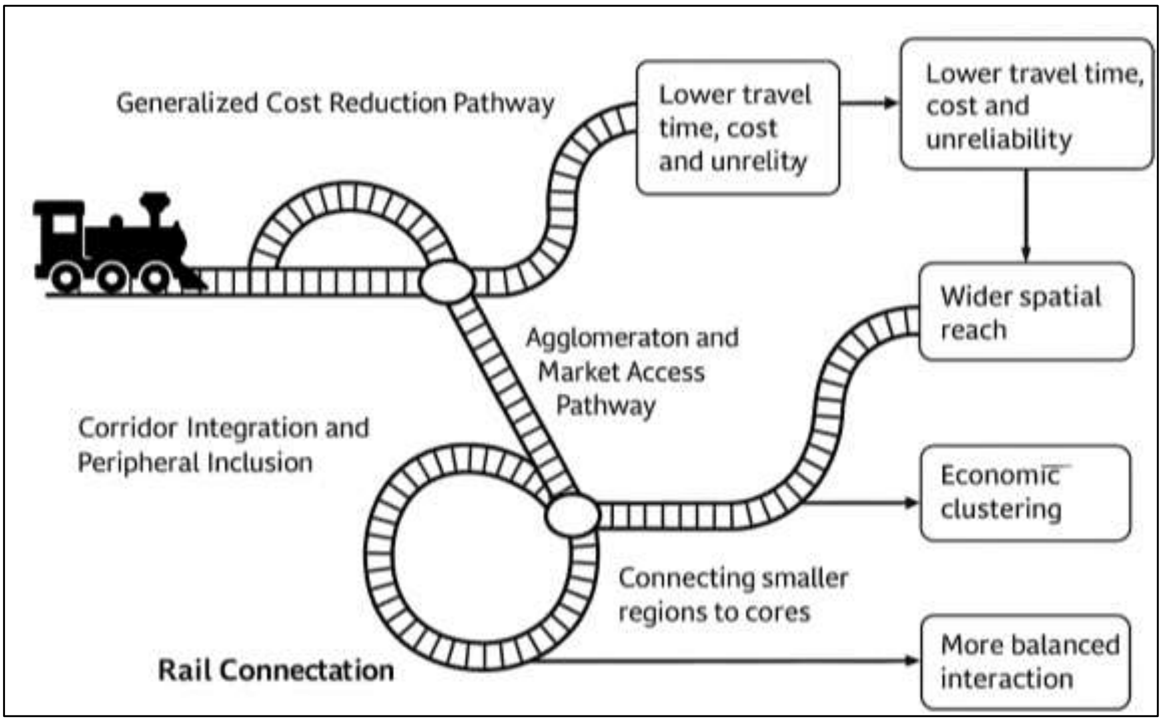
Across these conceptual foundations, the literature converges on a measurement logic that explains why systematic quantitative review is feasible and necessary. Connectivity studies relying on accessibility, interaction intensity, and performance indicators offer comparable evidence because they trace rail impacts through stable dependent-variable families that can be harmonized into shared effect categories (Palmatier et al., 2018). Accessibility measures translate rail investment into changes in reachable opportunities and market potential, enabling cross-region comparison of how corridor improvements alter spatial advantage. Interaction measures quantify how rail reshapes flows between cities and regions, allowing synthesis of corridor-level passenger responses and freight throughput changes tied to infrastructure scale. Network performance metrics bridge these traditions by showing how consistent movement strengthens functional ties even when average travel times shift modestly, highlighting the importance of reliability and frequency as connectivity drivers. Resilience studies provide equally structured quantitative outputs: robustness and redundancy analyses produce indices of vulnerability reduction and alternate-path availability, while recovery-focused work yields time-based and cost-based measures of restoration aftershocks (Estoque et al., 2019). Economic continuity research completes the conceptual chain by linking transport access and reliability to regional resistance and recovery in employment and production, allowing systematic reviews to map indirect rail effects through measurable resilience correlates. Importantly, U.S. rail scholarship spans multiple spatial scales and project types, and findings repeatedly show that impact magnitudes vary with baseline density, corridor maturity, and network structure. These contextual conditions are routinely measurable and therefore can be coded as moderators in review protocols. As a result, the conceptual foundations of connectivity, resilience, and large-scale railway exposure together define a coherent quantitative terrain: railway investments act as network-scale interventions, and their consequences appear through a consistent suite of accessibility, interaction, performance, redundancy, recovery, and economic stability measures across U.S. regions (Wiig et al., 2020). This coherence supports a systematic review that can aggregate evidence while preserving the heterogeneity that characterizes American railway impacts.

Theoretical Pathways Linking Rail to Connectivity

The theoretical literature linking rail to regional connectivity begins with the generalized cost reduction pathway, which interprets rail investment as a structural intervention that lowers the overall burden of movement between places. Generalized cost is not restricted to monetary fare or freight rate; it also includes time expenditure, schedule constraints, transfer penalties, perceived comfort, reliability risk, and the opportunity costs of uncertainty (Xu et al., 2019). When large-scale railway upgrades reduce travel time, increase service frequency, or smooth delay variability, the effective distance between regions shrinks. Empirical research repeatedly shows that travelers and shippers respond to this lowered generalized cost through changes in trip-making and routing behavior. For passenger corridors, reductions in door-to-door travel time increase the attractiveness of intercity rail for both discretionary and work-related trips, shifting demand away from highways and short-haul aviation. Studies using elasticity frameworks demonstrate that ridership is typically sensitive to both travel time and service frequency, meaning that even modest improvements in time competitiveness can yield sizable proportional gains in corridor usage when combined with more predictable schedules. For freight systems, lower generalized costs manifest as improved delivery reliability, shorter dwell times at terminals, and reduced congestion-related queuing, all of which raise the expected value of rail relative to trucking for longer hauls and bulk commodities (Burkhalter & Adey, 2020). This generalized cost mechanism affects connectivity through measurable spatial reach: when time and reliability improve, a larger set of destinations becomes practical within the same daily or weekly activity constraints, expanding labor-market ranges and business-to-business service areas. The literature highlights that the accessibility gains created by generalized cost reductions are not uniform across space. Regions already near rail nodes tend to realize immediate improvements in reachable opportunities, while more distant or historically disconnected regions may experience larger proportional accessibility gains because the relative travel impedance drop is greater. Another consistent finding is that reliability improvements often amplify connectivity impacts beyond what average time savings alone would predict (Chan et al., 2021). Reduced variance in travel time stabilizes planning for commuters, firms, and logistics operators, causing connectivity to rise through predictability as well as speed. This pathway is therefore treated as the most direct and observable channel by which rail investments translate into measurable connectivity outcomes.

A second pathway emphasized in theory and quantitative work is the agglomeration and market access pathway, which frames rail connectivity as an engine of spatial economic reorganization. Here, the key mechanism is that large-scale rail investments expand effective market size by lowering travel frictions between firms, workers, and consumers (Fan et al., 2019). When rail corridors provide faster and more reliable movement, firms can serve larger customer bases and draw from wider labor pools without fully relocating. This expanded reach increases the payoff to clustering because proximity to rail-enhanced accessibility nodes yields competitive advantages. Studies grounded in urban and regional economics show that improved market access is linked to densification of firms, rising productivity, and stronger specialization in regions positioned along upgraded corridors. Quantitatively, these impacts are reported through changes in firm density near stations or terminals, shifts in employment concentration, and measured productivity gains in access-sensitive sectors such as advanced manufacturing, logistics, tourism, and knowledge-intensive services (Cats, 2017). The logic is cumulative: rail lowers spatial transaction costs, which raises interaction frequency, which increases the returns to co-location and multi-firm ecosystems. These changes are not limited to metropolitan cores; intermediate cities located within upgraded rail ranges may gain new agglomeration roles by becoming practical subcenters within larger corridor economies. The literature also distinguishes between passenger-driven and freight-driven agglomeration effects. Passenger rail tends to reshape labor-market integration and service-sector clustering, while freight rail capacity and terminal modernization support industrial agglomeration through cheaper and more reliable shipment of inputs and outputs. Panel and shift-share analyses in prior studies show that markets with sustained rail improvements often experience gradual reweighting of regional output toward higher-value and access-dependent industries. Importantly, the pathway does not treat connectivity as merely movement; it treats connectivity as access to economic scale (Blanquart & Koning, 2017). Thus, the market access mechanism implies that the influence of rail on connectivity can be detected through measurable economic reconfiguration that accompanies accessibility gains, including productivity differentials, industry clustering patterns, and corridor-level output shifts tied to changes in transport impedance (Zhang et al., 2017).

Figure 4: Rail Connectivity and Resilience Pathways



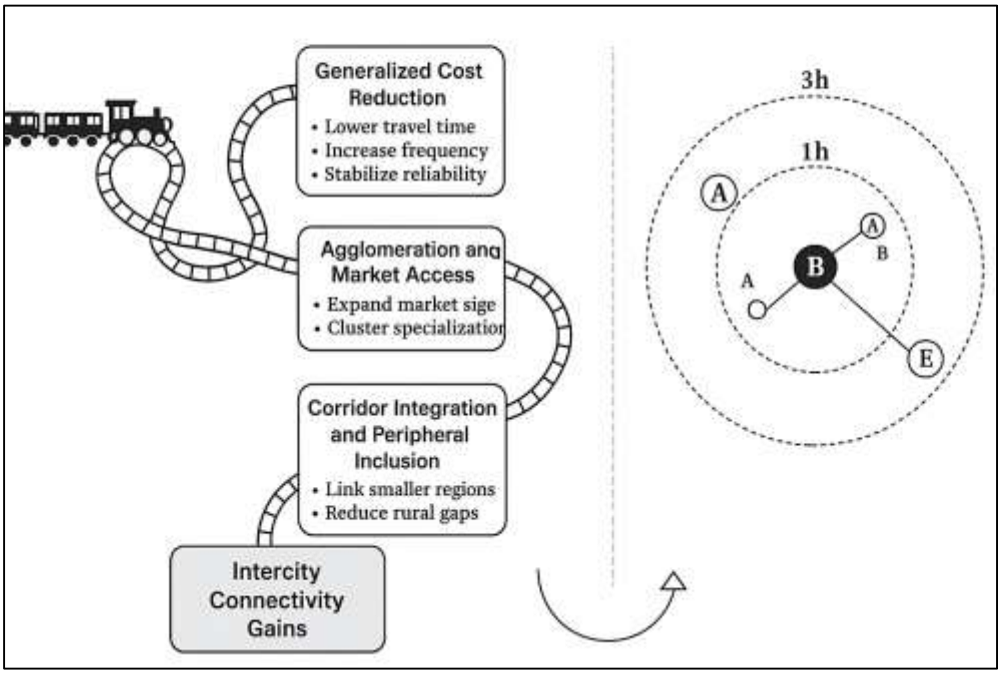
The corridor integration and peripheral inclusion pathway adds a territorial and distributive dimension to connectivity theory, focusing on how rail networks link smaller regions to dominant cores and re-balance spatial interaction (Jiao et al., 2017). In this perspective, large-scale railway infrastructure is a corridor-forming force that creates continuous chains of accessibility across multiple cities and subregions rather than isolated point-to-point improvements. The core mechanism operates through integration: rail upgrades reduce perceived and real separation between metropolitan hubs and surrounding small or mid-sized cities, enabling daily or frequent interchange that was previously impractical. Quantitative studies show that when corridor services add frequency, shorten journey times, and improve transfers, interregional commuting shares rise and multi-directional travel becomes more common (He et al., 2021). Peripheral inclusion is achieved when historically less-connected counties or micropolitan areas gain realistic access to metropolitan labor markets and specialized services, closing rural–urban accessibility gaps. The literature documents that such inclusion effects can be measured by reductions in accessibility inequality across corridor regions, by growth in cross-boundary commuting flows, and by increases in intercity trip volumes involving secondary nodes (Zhang et al., 2020). Freight corridor integration works similarly but through commodity-linkage systems. When rail capacity expansions or terminal investments allow peripheral production zones to connect more reliably to ports, distribution hubs, and consumer regions, peripheral areas become functionally closer to national and global markets. This inclusion can be tracked through changes in freight flow intensity, diversification of shipment destinations, and increases in regional export participation. Another important theoretical point is that corridor integration is not just additive. Many studies emphasize network effects, where connecting multiple smaller nodes to a core produces indirect accessibility gains between peripheral nodes themselves, enabling new lateral interactions that strengthen regional cohesion. Connectivity improvement therefore spreads along the corridor and across adjacent networks, producing measurable regional interaction intensification that exceeds local project boundaries (Zhu et al., 2018). This pathway is central for U.S. synthesis because the national geography includes many mid-sized cities and rural regions positioned between major metros, where corridor upgrades can shift the functional structure of entire regions.

Across the three pathways, the literature suggests that rail-driven connectivity emerges through overlapping behavioral, economic, and network dynamics that are measurable in distinct but compatible ways. Generalized cost reductions act first through traveler and shipper responses to lower time and monetary burdens, generating direct accessibility and demand shifts (X. Wang et al., 2017). Agglomeration and market access effects follow by translating those accessibility gains into wider economic reach and clustering incentives, leading to observed changes in productivity, firm location patterns, and regional output composition. Corridor integration and peripheral inclusion widen the spatial footprint of these effects by embedding smaller regions into higher-order systems of movement and trade, measured through shrinking accessibility disparities and rising interregional flow shares. Quantitative studies repeatedly show that the pathways reinforce one another. For example, time and reliability improvements can spark ridership and freight growth, which strengthens corridor interaction, which in turn supports agglomeration near well-connected nodes. Similarly, increased market access can raise demand for corridor services, feeding back into utilization and further justifying service intensification (Jiang, 2017). The literature also emphasizes that the strength of each pathway depends on baseline conditions such as pre-existing network density, metropolitan size, industrial structure, and the availability of competing modes. In high-density corridors, generalized cost improvements often translate quickly into observed ridership elasticities and interaction gains, while in lower-density regions connectivity gains may appear more strongly through peripheral inclusion and gradual market access expansion. Another recurring theme is that operational enhancements—especially service frequency and reliability—often trigger larger connectivity gains per unit investment than speed increases alone, because they reduce schedule friction and uncertainty that constrain practical spatial reach (Bombelli et al., 2020). Taken together, the theoretical pathways provide a coherent explanatory structure for systematic review by specifying how different categories of rail exposure are expected to influence accessibility measures, interaction volumes, and corridor performance indicators across U.S. regions, allowing evidence to be organized in a way that preserves both causal logic and measurable outcomes.

Empirical Evidence on Passenger Rail and Connectivity

Empirical evidence on intercity passenger corridors in the United States shows a consistent orientation toward quantifying how large-scale rail investments translate into measurable connectivity gains along specific routes and across broader regions (J. Liu et al., 2020). The most common evaluation designs are before–after comparisons, panel regressions using corridor-year or state-year observations, and quasi-experimental difference-in-differences approaches that compare treated corridors to similar non-treated corridors. Across these studies, ridership change is the most frequently reported outcome, often expressed as proportional shifts following infrastructure upgrades, service restorations, or schedule intensification. Corridor analyses repeatedly document that ridership response is tied to a bundle of improvements rather than a single attribute: reductions in end-to-end travel time, improved on-time performance, added departures, station enhancements, and smoother transfers (K. Wang et al., 2020). Mode diversion rates provide a second core metric, capturing the extent to which rail draws users away from highway travel and short-haul flights. Empirical findings show meaningful diversion where intercity rail reaches a competitive time window and where station access is convenient within metropolitan areas. Reliability improvement is also central in corridor evidence, with studies using operational logs and passenger performance reports to calculate changes in delay frequency, average lateness, and travel-time variability. Results commonly indicate that reliability upgrades produce connectivity benefits beyond those implied by average speed gains, because predictable travel expands practical trip-making for work, education, and medical purposes. A fourth cluster of intercity corridor outcomes focuses on accessibility gain, measured through changes in the number of jobs or essential services reachable within realistic time thresholds (Zhu et al., 2018). Empirical studies note that rail corridor improvements often produce uneven accessibility effects across cities: core metropolitan nodes typically realize large absolute increases in reachable opportunities, while intermediate cities and smaller regional centers often experience larger proportional gains because rail reduces a greater share of their baseline travel impedance. Overall, intercity corridor evidence portrays passenger rail as a connectivity amplifier that operates through ridership expansion, measurable mode substitution, reliability stabilization, and systematic enlargement of regional opportunity fields.

Figure 5: Passenger Rail Connectivity Evidence Framework



Evidence on commuter and metropolitan rail expansions further supports the connectivity narrative, though at finer spatial scales and with stronger emphasis on labor-market accessibility and congestion substitution. Large-scale urban rail projects are typically evaluated using station-area accessibility models, regional travel-demand datasets, and longitudinal ridership and traffic measures (Pan et al., 2017). The most common quantitative outcomes include station-level employment access expansion, which captures how new lines, extensions, or capacity upgrades change the number of jobs reachable within peak-period travel times. Studies consistently show pronounced accessibility gains in neighborhoods newly connected to high-frequency rail, with the strongest effects appearing where stations integrate well with feeder transit or walkable catchments. Peak congestion substitution effects are another recurrent endpoint, assessed through changes in highway volumes, peak-period speeds, or vehicle miles traveled in corridors served by expanded rail. Empirical findings point to substitution when rail provides high reliability and headway advantages during congested periods, enabling commuters to shift away from driving or to re-time trips (de Langen et al., 2017). Some studies also track corridor-wide redistribution rather than net reduction, indicating that rail expansions can reallocate roadway pressure spatially by changing commuting geography. A more distribution-sensitive strand examines accessibility elasticity by income or region, when data permit. These papers explore whether accessibility improvements translate evenly across socioeconomic groups or whether gains concentrate around higher-income station areas. Quantitative evidence often indicates that accessibility changes are spatially patterned by housing markets, land-use context, and station siting, meaning connectivity gains at the metropolitan scale may coexist with variability in household-level access benefits. Another robust empirical theme is that commuter and metro rail expansions generate multilayered connectivity impacts: they increase access to employment centers, intensify cross-subregional commuting, and enhance intermodal reach by linking local networks to intercity corridors or major airports (Redondi et al., 2021). The commuter and metropolitan evidence therefore complement intercity findings by showing how large-scale passenger rail projects strengthen regional connectivity through measurable access growth and peak-period mobility stabilization within urban systems.

A third empirical area compares service frequency and speed effects, and the U.S. literature provides a relatively clear quantitative message: frequency and reliability often drive connectivity returns more strongly than speed alone. Studies that estimate standardized coefficients or marginal effects typically treat travel time, headway, and on-time performance as competing predictors of ridership or accessibility change (Zhu et al., 2021). The resulting evidence indicates that additional departures reduce schedule friction and waiting uncertainty, making rail usable for a wider set of trip purposes and increasing corridor interaction density. Speed improvements matter most where they shift rail into a competitive travel-time band relative to driving or flying, yet even in those cases, empirical models often show that speed benefits are magnified when paired with better frequency. Marginal accessibility gains per added departure are especially visible in corridors that already have reasonable travel times but limited schedule choice. In such settings, increasing daily train counts expands the feasible time windows for commuting, business trips, and same-day returns, effectively enlarging opportunity access without altering physical distance (Ingvardson & Nielsen, 2018). Conversely, speed upgrades show larger marginal influence in longer corridors or where prior travel times were high enough to deter rail use altogether. Empirical comparisons also underline that frequency improvements tend to produce steadier gains across multiple stop-pairs along a corridor, whereas speed gains may concentrate benefits between major endpoint cities. This distinction matters for regional connectivity because intermediate cities often rely on schedule availability more than top speed for practical regional integration (Jiao et al., 2017). Taken together, the frequency-versus-speed evidence aligns closely with corridor and metro findings: passenger rail strengthens connectivity through a compound service quality channel in which reliability and schedule richness frequently deliver larger measurable returns per unit change than speed increases in isolation.

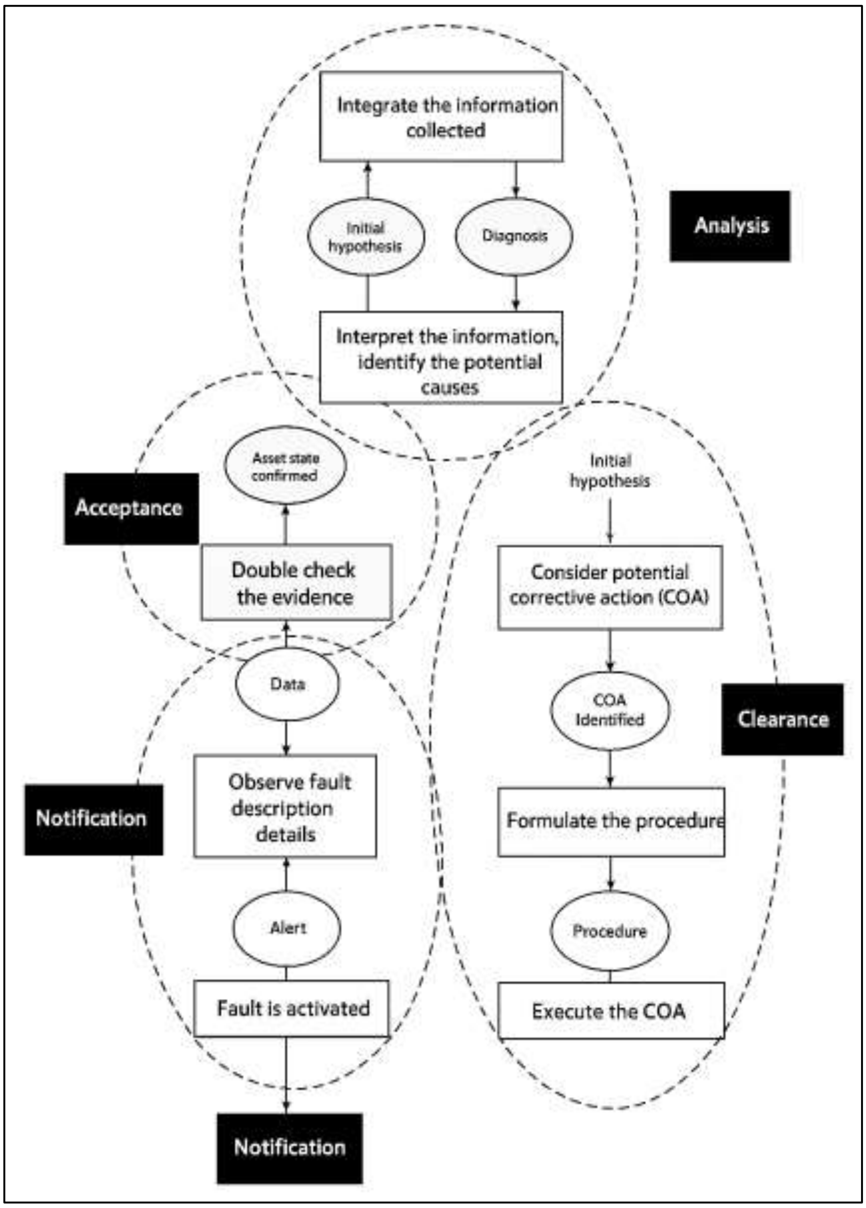
Empirical Evidence on Freight Rail and Connectivity

Freight rail connectivity in the United States has been examined extensively through studies of mainline capacity expansion and reliability improvement, with a shared premise that large-scale infrastructure changes reshape how regions are functionally linked through commodity movement. Empirical research on mainline additions, siding extensions, double-tracking, signal modernization, bridge and tunnel upgrades, and grade separations commonly evaluates connectivity through changes in network throughput, system delay behavior, and reliability stability (de Langen et al., 2017). Across multiple corridor and system-level investigations, throughput is treated as the clearest expression of enhanced connectivity because it reflects the network's ability to carry more regional economic exchange without proportionate increases in friction. Studies using operational records and carrier performance datasets show that capacity upgrades tend to support measurable increases in annual tonnage, train counts, and loaded car-miles, especially in corridors connecting energy basins, agricultural belts, and manufacturing regions to ports and major consumption markets. Reliability-focused work complements throughput evidence by emphasizing that connectivity strengthens when freight movement becomes predictable. Quantitative assessments of delay trends often report reductions in terminal dwell time, fewer hours lost to congestion bottlenecks, and lower sensitivity of shipment times to peak demand or weather disturbances (Esposito et al., 2020). Reliability variance reduction, even when average speed gains are modest, is consistently associated with stronger logistics connectivity because stable arrival windows enable tighter inventory control, more frequent shipment cycles, and improved interregional supply coordination. Several studies also highlight network spillovers: mainline upgrades on high-volume routes reduce congestion that would otherwise reverberate across adjacent corridors, so connectivity gains appear not only on the upgraded segment but across broader regional networks. Another recurring empirical point is that capacity improvements preserve connectivity during disruptive conditions. Even though these studies may not frame their models explicitly as resilience inquiries, their findings show that expanded passing capacity and modernized control systems reduce the probability of network-wide gridlock during shocks, enabling alternative routing and faster restoration of flow (Boonekamp & Burghouwt, 2017). Overall, mainline capacity and reliability research portrays freight rail as a backbone of regional connectivity whose large-scale upgrades manifest through higher flow capability, lower delay exposure, and more stable performance across routine and disrupted operating environments.

A second major empirical stream evaluates freight connectivity through intermodal terminals and port–hinterland linkages, treating large terminals and corridor interfaces as spatial hinges that convert rail capacity into regional and international access (Ambra et al., 2019). Intermodal research typically examines projects such as terminal expansions, new inland ports, double-stack clearance programs, yard modernizations, and last-mile rail connections to seaports and logistics parks (K. Wang et al., 2020). The dominant connectivity outcome in this literature is intermodal share change, interpreted as the degree to which rail captures a larger proportion of long-haul container and trailer traffic relative to trucking. Studies using commodity-flow surveys, port statistics, and terminal throughput records show that investments improving rail access to ports reduce drayage friction, enlarge the effective hinterland, and make rail a more competitive mode for inland regions. This shift is measurable through rising container-on-rail proportions, higher rail-originating port volumes, and expanded inland distribution reach from coastal gateways. Another common outcome is export flow growth tied to access improvements. Empirical work on Gulf, Atlantic, and Pacific gateways indicates that when rail corridors gain capacity and terminals gain lift or staging capability, inland manufacturers and agricultural exporters experience lower logistics cost and improved schedule reliability, which supports larger and more diverse export flows (Woodburn, 2017). Terminal studies also underline connectivity as a network property rather than a local one. A well-placed inland terminal can reconfigure regional exchange patterns by shortening effective distance to ports and by consolidating freight for high-capacity rail line-hauls, thereby pulling peripheral regions into wider trade circuits. Several investigations of inland port development in the Midwest and Southeast demonstrate that terminal-led rail connectivity can redistribute supply-chain geography, shifting warehouse clusters and distribution centers toward rail-served nodes. The evidence further suggests that intermodal connectivity benefits are strongest where terminals are integrated with highway access, customs processes, and regional industrial zones, because multimodal frictions can cancel out rail gains if not addressed (Fageda & Gonzalez-Aregall, 2017). Taken together, the intermodal and port–hinterland literature shows that large-scale terminal investments convert mainline capacity into measurable regional access advantages, visible through intermodal market share growth, inland export participation, and widening of hinterland influence for U.S. ports.

A third body of freight-rail research connects infrastructure scale to regional productivity and industrial outcomes, treating connectivity as an economic-enabling condition that can be quantified in output and employment metrics. Many studies in transportation economics and regional development find that rail capacity and access improvements correspond with gains in regional productivity, especially in heavy manufacturing, resource extraction, and export-oriented agriculture (Iimi et al., 2019). The mechanism described across these works is that freight rail reduces the generalized cost of shipping bulk and containerized commodities over long distances, expanding feasible market reach for firms and lowering input delivery risk. Empirical analyses using panel data at the county, metropolitan, or state level often report that regions experiencing sustained rail capacity improvements show higher growth in industrial output, greater logistics efficiency, and improved competitiveness in national and international markets. Output effects are typically more pronounced where rail serves as the dominant long-haul mode, such as in grain corridors, coal and energy routes, chemical and auto supply chains, and intermodal consumer-goods movements between ports and inland megaregions (Behiri et al., 2018). Employment growth tied to freight access is another recurring finding. Studies focusing on rail-served industrial clusters and terminal regions show that improved freight connectivity supports job expansion in manufacturing, warehousing, and logistics services, and can stabilize employment during sectoral downturns by maintaining cost-competitive market access. Research on firm location and industrial geography also indicates that large-scale rail connectivity can influence where production concentrates, with firms favoring nodes that offer reliable, high-capacity rail access for inbound inputs and outbound shipments. Several investigations note that these benefits are not automatic: productivity gains depend on whether capacity investments eliminate true bottlenecks, enable consistent cycle times, and align with commodity flows that are rail-advantaged (Ingvardson & Nielsen, 2018). Nonetheless, the weight of evidence suggests that freight rail functions as a regional productivity platform, and large-scale upgrades register as measurable economic connectivity effects through output growth, employment expansion, and strengthened industrial clustering along upgraded corridors and terminal nodes.

Figure 6: Freight Rail Connectivity Analysis Framework



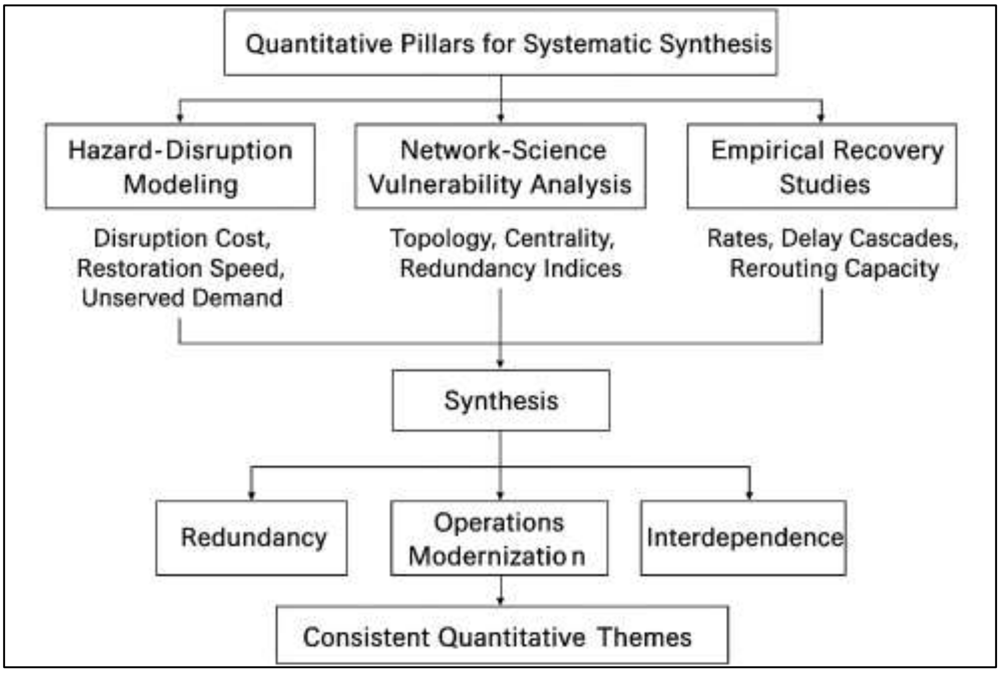
Synthesizing across these empirical domains reveals a coherent picture of how freight rail infrastructure strengthens U.S. regional connectivity through mutually reinforcing operational and economic channels. Mainline capacity and reliability studies show that connectivity improves when corridors can carry larger and steadier volumes, reducing congestion exposure and enabling predictable interregional exchange (Chen & Lin, 2020). Intermodal and port–hinterland studies demonstrate that connectivity is intensified when terminals and corridor interfaces expand the practical reach of inland regions to global gateways, increasing rail's intermodal role and widening export participation. Productivity and industrial studies confirm that these transportation improvements translate into measurable economic outcomes, with rail access shaping regional output performance and employment trajectories in access-sensitive sectors. Across at least a decade of corridor evaluations, systemwide operational analyses, inland port case studies, and regional econometric investigations, a consistent empirical theme is that reliability and capacity act together: higher throughput without reliability improvement yields weaker connectivity gains, while reliability improvement without adequate capacity can be absorbed by demand growth and thus fade (Sun et al., 2019). Another cross-cutting finding is that freight connectivity benefits frequently spill beyond the immediate project footprint, affecting parallel routes, adjacent regions, and downstream logistics nodes because rail networks are tightly interdependent. Studies also show that benefits vary by baseline conditions—such as pre-investment congestion, commodity mix, and proximity to ports or industrial bases—so large-scale rail investments can generate different magnitudes of connectivity and productivity gains across U.S. regions (Mimeur et al., 2018). Still, the empirical literature converges on the interpretation that freight rail infrastructure is a core determinant of regional linkage strength. Its large-scale modernization and expansion are consistently associated with enhanced corridor flow capability, higher intermodal integration, stronger port–inland exchange, and measurable economic reinforcement across connected regions.

Quantitative Evidence on Rail and Resilience

Quantitative evidence on rail and resilience in the United States begins with hazard-disruption modeling studies that treat railway networks as systems exposed to probabilistic and scenario-based shocks. This literature uses simulation and scenario analysis to estimate how passenger and freight rail perform when confronted with events such as hurricanes, riverine floods, coastal storm surge, extreme heat, wildfire, seismic disturbance, equipment failure, and cyber or power disruptions (Bešinović, 2020). The central idea is that resilience can be observed through how much performance is lost, how widely the loss spreads, and how quickly the system can restore service. Many modeling studies build synthetic disruption cases by disabling specific links, nodes, terminals, or control assets and then tracking system outcomes across time. The most common quantitative outputs include expected disruption costs, which combine delay penalties, detour costs, cargo spoilage risk, passenger time losses, and broader economic spillovers; recovery time, expressed as the duration required for throughput or service to regain a defined share of baseline; and unmet origin–destination demand under shock, which captures the volume of passenger trips or freight flows that cannot be served within feasible constraints during the disruption window (Woodburn, 2019). Findings across multiple modeling efforts show that resilience gains are strongly linked to the presence of alternative routings and operational flexibility. Corridors with parallel tracks, bypass routes, or nearby intermodal substitutes tend to exhibit lower modeled disruption cost and smaller shares of unmet demand, even when hazard intensity is high. Another repeated observation is that improvements in control systems, dispatch efficiency, and terminal capacity often reduce disruption effects as much as physical hardening, because they enable rapid reallocation of trains and avoid secondary congestion cascades. Modeling results also show that freight and passenger resilience are interdependent on shared corridors: a disruption that begins as a freight bottleneck can propagate to passenger delays and vice versa, amplifying total costs beyond the immediate damaged segment (Fabella & Szymczak, 2021). Across the hazard-disruption simulation tradition, resilience is therefore treated as a measurable, scenario-sensitive response capacity that can be summarized through disruption cost, restoration speed, and demand fulfillment under stress, making these studies a core quantitative pillar for systematic synthesis.

Network-science and vulnerability studies provide a second quantitative foundation by analyzing railway systems as complex networks whose resilience depends on topology, redundancy, and critical-link structure. Rather than emphasizing detailed hazard physics, these studies focus on how the configuration of nodes and links shapes the system's tolerance to removal or failure. Typical methods include graph removal experiments, where links or nodes are disabled according to targeted rules (such as removing the most central links first) or random rules (simulating diffuse risk), and centrality stress tests, which measure how network importance shifts under failure (Hale & Heijer, 2017). From these experiments, studies compute outcomes such as changes in redundancy indices, which quantify the availability of alternate paths between important origin–destination pairs; impacts on critical-link failure probability, often derived from how heavily certain links concentrate flows; and betweenness loss after targeted failures, which indicates how much of the network's routing capacity is destroyed when high-centrality components are compromised. Empirical applications to U.S. rail systems repeatedly show that resilience is not evenly distributed: a relatively small set of high-centrality bridges, tunnels, mountain passes, coastal segments, and terminal approaches can carry an outsized share of national or regional flow (Janić, 2018). When these components are removed in simulations, fragmentation rises sharply and effective travel distances between regions increase even if nearby track remains intact. Another consistent pattern is that redundancy is frequently asymmetric: freight networks may have multiple routing options across broad geographies, while passenger networks often rely on narrower corridor spines, creating different vulnerability profiles even within the same physical territory. Studies also show that network resilience improves when investments reduce single-point dependencies. Adding passing segments, reactivating secondary routes, or increasing interoperability between lines tends to raise redundancy indices and reduce the likelihood that any one link failure will sever regional connectivity (T. Wang et al., 2020). Network-science work further highlights that resilience is not solely a function of how much infrastructure exists but of how it is arranged; dense networks with poorly aligned alternates may still be vulnerable, while sparser networks with strategically placed bypasses can be relatively robust. Because these approaches yield standardized metrics that are comparable across cases, they are especially valuable in systematic review for linking infrastructure configuration to measurable resilience outcomes.

Figure 7: Quantitative Rail Resilience Framework Synthesis



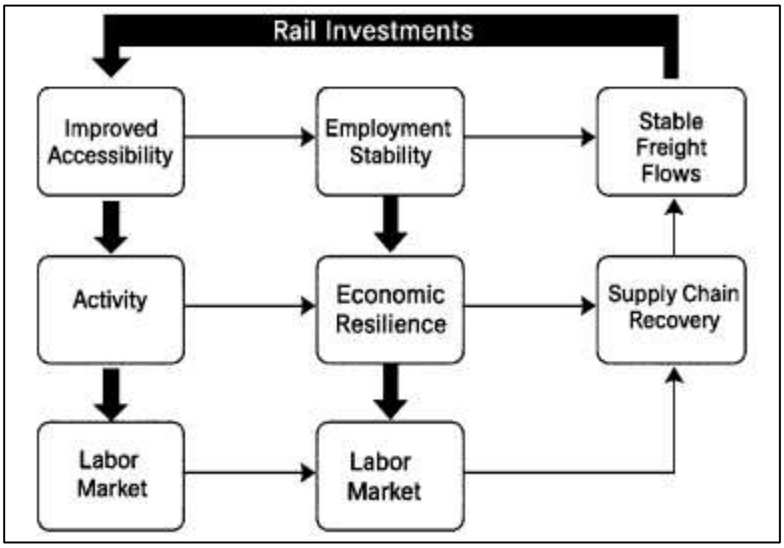
A third strand centers on empirical recovery and real-event studies, which use observed disruptions and operational data to quantify how rail systems actually respond to shocks. These studies rely on time-series recovery analysis, dispatch and delay logs, shipment tracing, ridership records, and throughput statistics to detect resilience behavior before and after disruptions or investments. Instead of simulated scenarios, they examine real hazard episodes—major storms, floods, derailments, bridge outages, labor stoppages, or prolonged heat restrictions—and measure the depth and duration of performance loss (Rungskunroch et al., 2021). Common quantitative outcomes include throughput rebound rates, which track how quickly freight tonnage or train counts return toward baseline levels; delay propagation reduction following modernization, which captures whether improvements dampen the spread of lateness across a network; and rerouting feasibility metrics, which estimate how much traffic can be diverted to alternates without severe secondary congestion or capacity collapse. Across multiple cases, empirical evidence shows that recovery trajectories depend on both physical redundancy and operational readiness. Rail systems with accessible detours and pre-planned contingency dispatching display steeper rebound slopes and shorter recovery periods (Liu et al., 2021). Conversely, networks with narrow choke points or limited yard flexibility often experience prolonged recovery even after the damaged asset is restored, because backlogs and crew or equipment imbalances persist. Several studies also show that modernization investments—especially those improving signaling, positive train control coverage, terminal throughput, and track condition—reduce routine delay accumulation, and this operational stability translates into better recovery performance during extreme events. Another reliable observation is that passenger and freight recovery interact: restoring one service type can either accelerate or slow the other depending on dispatch priority and corridor saturation, producing measurable differences in rebound rates (Cantelmi et al., 2021). Real-event studies therefore ground resilience claims in observed performance time paths, making them a crucial complement to modeling and network-science work. They provide direct evidence of how large-scale rail investments alter the speed, smoothness, and completeness of recovery in actual U.S. operating environments.

Synthesizing across hazard-disruption modeling, network-science vulnerability analysis, and empirical recovery studies yields a coherent quantitative picture of how rail resilience is generated and measured in the United States. Modeling studies clarify the magnitude of potential losses and recovery benefits under diverse shocks, offering standardized outputs on disruption cost, restoration time, and unserved demand (Chen & Rose, 2018). Network-science studies explain why those losses concentrate spatially by revealing how topology, centrality, and redundancy structure vulnerability, and they provide comparable indices of redundancy change and critical-link sensitivity. Empirical recovery studies validate these mechanisms through observed rebound rates, reduced delay cascades after improvements, and measured rerouting capacity in real disruptions. Across this combined evidence base, several consistent quantitative themes appear. First, redundancy is a dominant driver of resilience: where alternatives exist and are operable at scale, disruptions generate lower systemwide losses and faster recovery. Second, operational modernization matters as much as physical expansion; investments that increase dispatch flexibility and terminal throughput often deliver measurable resilience dividends even without large new route-miles (Gherghina et al., 2018). Third, resilience benefits frequently spill beyond the upgraded segment because rail networks are interdependent; improving a bottleneck can reduce delay propagation and recovery time across entire regions. Fourth, resilience effects differ between freight and passenger services due to contrasting network geometries and priority rules, meaning systematic review must treat these subsystems as distinct but interacting layers. Overall, the quantitative resilience literature portrays railways as critical regional lifelines whose ability to absorb shocks and recover can be observed through stable families of cost, performance, redundancy, and recovery metrics (Corman et al., 2018). This stability is what makes a systematic quantitative synthesis possible: despite differences in methods and contexts, studies repeatedly measure resilience in ways that can be harmonized to evaluate how large-scale railway infrastructure strengthens regional shock tolerance across the U.S.

Rail Investments and Regional Recovery

Rail investments are frequently linked to economic resilience through the channel of accessibility, where the ability of workers to reach diverse employment opportunities serves as a measurable buffer against labor-market shocks (Nelson et al., 2019). The literature in regional economics and transportation systems treats accessibility not simply as a mobility convenience but as a stabilizing capacity embedded in the spatial structure of a region. When large-scale rail projects reduce travel time, increase frequency, and improve reliability between residential areas and employment centers, they enlarge the feasible job-search radius for households. Quantitative studies that track employment volatility before and after connectivity improvements show that regions with stronger rail-based accessibility tend to experience smaller swings in unemployment during downturns, partly because workers can reallocate across a wider set of industries and locations without prohibitive commuting burdens (Janić, 2018). In metro-to-metro corridors, improved intercity rail makes cross-regional commuting and job switching more tractable, raising measured labor-market integration. This integration appears in empirical indicators such as increased cross-boundary commuting shares, higher interregional job matching rates, and tighter synchronization of wage and employment cycles across connected cities. After shocks—economic crises, large employer closures, or sector-specific contractions—regions with improved rail access often show steeper job recovery trajectories, reflecting faster reintegration of displaced workers into active labor markets (Tan et al., 2017). The literature emphasizes that these benefits are strongest where rail accessibility connects residents to multiple distinct employment clusters rather than a single dominant center. In such settings, rail provides redundancy in labor opportunity, reducing dependence on any one local sector. Another recurring finding is that reliability improvements matter as much as speed improvements: predictable rail schedules and low delay variance reduce the risk premium associated with longer commutes, making distant jobs viable over sustained periods (Bešinović, 2020). Thus, accessibility created by large-scale passenger rail tends to manifest in measurable reductions in employment volatility, improvement in post-shock recovery gradients, and intensified labor-market integration across regions, positioning rail as an economic shock absorber through mobility-based opportunity expansion.

Figure 8: Rail Investments and Economic Resilience

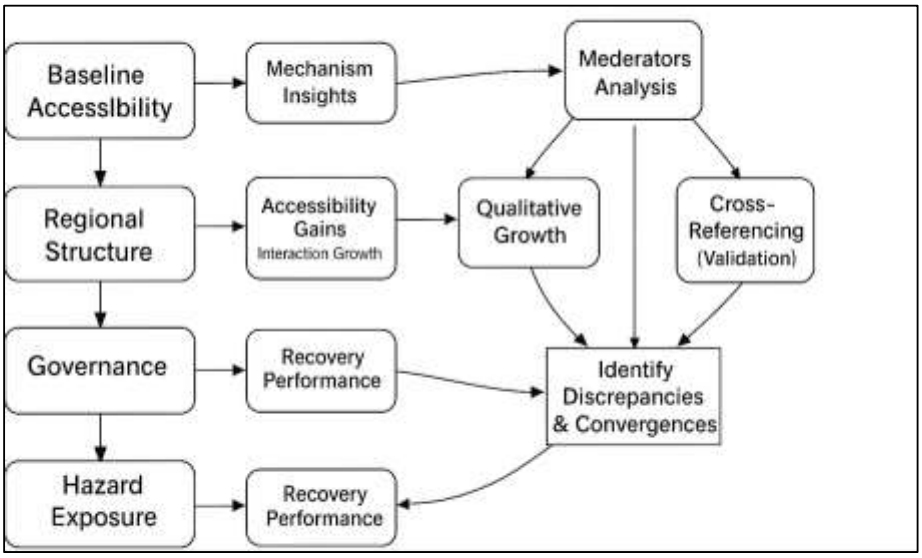


Freight continuity and supply-chain stabilization represent a second pathway by which rail investments support economic resilience and regional recovery. The freight-rail literature stresses that regional economies depend on steady input delivery and output distribution, and disruptions to logistics systems can propagate quickly into production losses, inventory shortages, and trade contraction (Tan, 2021). Large-scale rail investments that expand mainline capacity, modernize signaling, improve terminal throughput, and eliminate bottlenecks are repeatedly associated with more stable freight flows under both routine stress and extreme disruption. Quantitatively, resilience in this domain is observed through the speed of industrial production recovery after disruptions, the stabilization of inventory cycles, and the preservation of export performance relative to pre-shock trajectories. Industrial regions that rely on heavy or bulk transport—manufacturing belts, agricultural interiors, energy basins—often show faster rebound in shipment volumes when rail corridors provide reliable long-haul capacity even while other modes face congestion or damage (Jiao et al., 2021). Several empirical strands highlight that rail's contribution to continuity is not limited to absolute flow volume; it also lies in maintaining regularity of flow. Reduced dwell times, lower congestion delay sensitivity, and expanded rerouting options allow firms to sustain more predictable replenishment and distribution rhythms, which in turn dampen inventory volatility. Where intermodal terminals and port-hinterland rail links have been strengthened, regions often retain export participation more robustly aftershocks that constrain trucking or port operations, because rail can shift routing to alternative gateways or consolidate flows to maintain serviceability (Behiri et al., 2018). The literature also notes spillover effects: a capacity or reliability improvement on one strategic freight corridor can stabilize supply chains across multiple states by preventing network-wide congestion cascades. In recovery phases, this translates into higher throughput rebound rates and quicker restoration of commodity and container movement for connected regions (Magazzino & Maltese, 2021). Overall, freight-oriented rail investments are consistently interpreted as resilience assets because they preserve the continuity of industrial production and trade through measurable stabilization of flows, inventories, and export capacity.

Moderators and Sources of Heterogeneity

Moderators and sources of heterogeneity are central to interpreting quantitative findings on how large-scale railway infrastructure influences regional connectivity and resilience in the United States. The literature shows that rail investments do not produce uniform effects because regions differ in starting conditions, network form, institutional arrangements, and hazard environments. These differences shape both the size and the distribution of measured outcomes such as accessibility gains, interaction growth, reliability improvement, and recovery performance after disruptions (Santoro et al., 2020). As a result, systematic review designs commonly isolate moderators to explain why two projects of similar physical scale can yield different connectivity or resilience returns. Heterogeneity is not treated as statistical noise; it is interpreted as evidence that rail impacts are conditional on context. Moderator analysis therefore becomes a core analytical step in quantitative synthesis, allowing the evidence base to be grouped into comparable sets and enabling clearer inference about the pathways through which rail affects regional systems. Across studies, four moderator clusters recur with particular consistency: baseline accessibility conditions, regional structural characteristics, governance and ownership context, and hazard exposure environment (Kim & Mokhtarian, 2018). Each moderator cluster links to measurable mechanisms, and together they account for a substantial share of cross-study variance in reported effect sizes. A systematic review that includes these clusters is able to organize findings into interpretable patterns rather than averaging fundamentally different regional settings into a single undifferentiated estimate. Baseline accessibility is one of the most frequently observed sources of variation in rail impacts. Pre-investment access levels define how connected a region already is before a project is implemented, while network density captures the depth of existing rail service and its integration with surrounding transport systems (Zink et al., 2020). Regions with high baseline accessibility—often large metropolitan corridors already served by multiple daily trains, intermodal terminals, and dense highway networks—tend to show large absolute gains when rail is upgraded. Their accessibility total may rise substantially in terms of jobs, services, and markets reachable, because incremental improvements operate on already high mobility demand and a wide destination set. In contrast, regions with lower baseline accessibility—smaller cities, rural counties, and historically under-served corridors—frequently show larger proportional gains. When a region begins from a low access base, even modest time savings or frequency additions can double the set of realistically reachable opportunities, producing high percentage changes in access indices and interaction rates (Ardito & Petruzzelli, 2017). The literature also suggests that baseline network density moderates' reliability and resilience outcomes: corridors within dense networks often have more routing options, so investments quickly translate into redundancy gains and reduced disruption sensitivity, while sparse networks may exhibit sharper vulnerability reduction only when projects create wholly new alternatives. Baseline accessibility thus shapes not only whether rail moves the needle, but also the form that "improvement" takes—absolute scale in already connected regions and proportional transformation in less connected ones.

Figure 9: Moderator Framework for Rail Impacts



Regional structure adds another layer of heterogeneity by conditioning demand, spatial interaction, and economic translation effects. Metro size is a strong moderator because population tiers correspond to trip generation, labor-market thickness, and the viability of high-frequency rail service. Large metros often yield higher ridership and interaction elasticities, so similar rail investments may produce stronger observed flow and accessibility effects than in smaller urban systems. Rural–urban classification further refines this pattern by capturing settlement dispersion and the spatial arrangement of opportunities (Aulbach et al., 2019). Urban regions typically show connectivity gains through frequency-driven trip intensification and congestion substitution, whereas rural regions show gains through expanded reach to higher-order services and markets rather than high daily ridership volumes. Industrial specialization also moderates freight and resilience effects by shaping what kinds of flows rail carries and how critical rail is to regional production continuity (Reangsing et al., 2021). Regions specialized in bulk commodities, manufacturing supply chains, or export agriculture often exhibit stronger freight throughput and logistics-reliability returns from capacity investments than service-oriented regions where rail freight plays a smaller role. On the passenger side, specialized tourism and education hubs may show outsized connectivity response relative to their size because rail access aligns with concentrated trip motives (Ludyga et al., 2020). Structural moderators therefore explain why rail investments can look highly effective in one region while appearing modest in another: the underlying population and economic architecture sets the ceiling and direction for measurable connectivity and resilience outcomes. In practice, these moderators help systematic reviews separate contexts where rail operates as a high-volume corridor engine from contexts where rail functions as a strategic access lifeline, ensuring that pooled findings preserve the real differences embedded in U.S. regional form.

Governance and ownership context is a third major moderator cluster, especially distinctive in the U.S. setting. Freight-owned versus shared corridors create different operational realities that directly affect observed impacts. Freight-owned mainlines can exhibit large freight connectivity and resilience gains from investments, but passenger outcomes vary depending on dispatch priority, slot allocation, and the degree to which passenger services are protected by agreements or infrastructure separation (Salyers et al., 2017). Shared corridors introduce interaction effects: a capacity or signaling upgrade aimed at freight may still increase passenger reliability by reducing congestion, while passenger-oriented grade separations or station reconfigurations can improve freight fluidity. State partnership intensity operates as another moderator because passenger rail in the U.S. relies on multi-level financing and coordinated planning. Corridors with deeper state involvement often achieve higher sustained frequencies, more consistent maintenance cycles, and better station-area integration, producing stronger accessibility and interaction effects than corridors where upgrades are isolated or episodic (Conn & Ruppar, 2017). Funding magnitude per mile is also a meaningful moderator because it approximates the depth of intervention; higher investment density is associated with more comprehensive modernization packages, which tend to yield larger reliability and resilience effects than light-touch improvements. Governance moderators thus explain heterogeneity that arises not from geography alone, but from how the rail system is managed, prioritized, and financed, influencing both what is delivered and how benefits propagate through networks (Ma et al., 2021). Systematic reviews that code these institutional conditions can more accurately interpret why effects differ between otherwise similar corridors, especially in mixed passenger–freight environments.

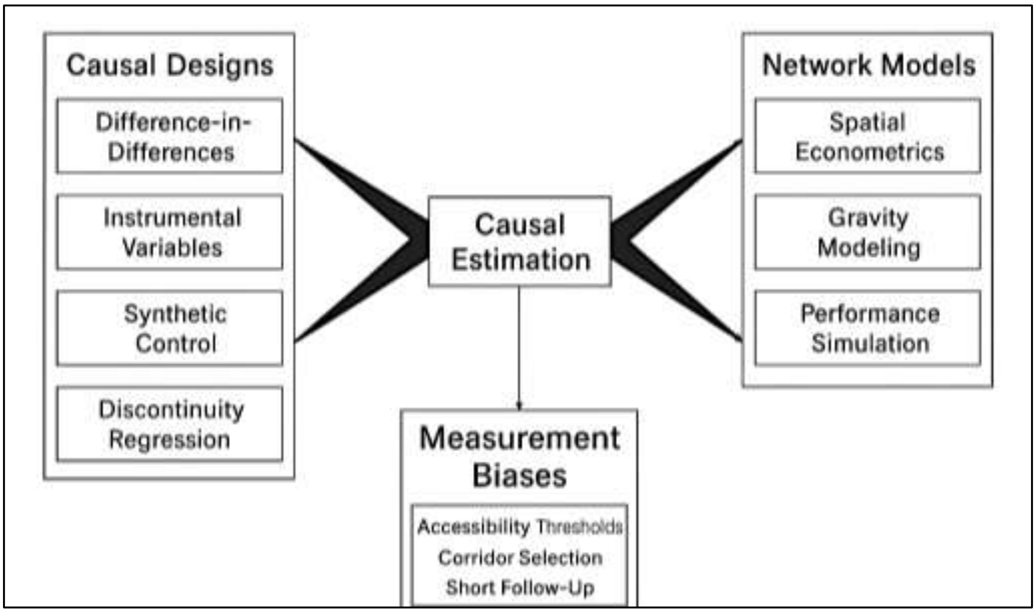
Hazard exposure context rounds out the heterogeneity framework by explaining why resilience effects differ across regions even when connectivity improvements appear similar. Flood, heat, and wildfire risk tiers alter the baseline probability and type of disruption a corridor face. Corridors in coastal floodplains or riverine basins encounter frequent washouts, storm surge, and track submersion risk, so resilience benefits from hardening or redundancy investments show up clearly through reduced closure time and quicker throughput recovery (Cabeza-Ramírez et al., 2020). Heat-exposed interior corridors face speed restrictions and track buckling stress, meaning resilience gains may be measured more through reliability stabilization and reduced seasonal performance volatility. Wildfire-risk corridors experience episodic but intense disruption patterns, so investments that improve rerouting feasibility or protect critical nodes produce measurable resilience dividends. Coastal versus inland positioning is a related moderator because coastal corridors often concentrate flows into narrow rights-of-way with limited alternatives, increasing chokepoint sensitivity, while inland corridors may have more latitude for alternate routing but face longer detour penalties (Bryan et al., 2021). Studies repeatedly show that resilience outcomes are strongest where the hazard environment is severe enough for improvements to be tested frequently and visibly, while lower-hazard corridors may still benefit but show smaller realized effects in short observation windows. Hazard context therefore reframes resilience heterogeneity as a function of exposure and testing frequency, not merely infrastructure quality. When systematic reviews incorporate hazard moderators, they can distinguish whether observed resilience gains reflect true network strengthening or simply differences in how often corridors face disruptive events (Castro et al., 2020).

Quantitative Method Patterns in Prior Research

Prior quantitative research on large-scale railway infrastructure and regional outcomes in the United States relies heavily on econometric causal designs to isolate the effect of rail investments from broader economic or demographic change. Across the literature, corridor upgrades, line reopening's, service intensifications, and terminal expansions are frequently treated as "treatments" occurring at identifiable points in time or within specific geographies (Munk et al., 2017). Difference-in-differences approaches dominate studies where researchers can observe treated corridors or counties before and after investment while comparing them to matched control areas that did not receive similar rail changes. These designs are used to estimate the net rail-related shift in ridership, freight throughput, accessibility, land value patterns, employment measures, or recovery performance aftershocks. Instrumental-variable strategies appear in studies confronting endogeneity in investment placement, especially where rail upgrades are more likely to occur in already-growing regions. In these cases, investigators search for historical routing constraints, political funding rules, engineering suitability, or legacy network features that predict rail investment but are not directly correlated with contemporaneous outcomes (Kan & Gero, 2017). Synthetic control designs are less common but increasingly visible in corridor-scale research where a single, high-profile rail project is evaluated by constructing a weighted composite of non-treated corridors that best reproduce pre-investment trends. This method is particularly useful for modern intercity passenger corridor upgrades or major intermodal hub developments that do not have obvious one-to-one control corridors. Regression discontinuity designs appear in a smaller subset of studies when rail funding eligibility, station spacing rules, boundary-based service changes, or port-hinterland program thresholds create sharp cutoffs that can approximate random assignment around the threshold. Across all these econometric families, extraction and synthesis in systematic reviews tends to focus on standardized effect representations that allow comparisons across different dependent variables (Flinton & Malamateniou, 2020). Studies typically report effects as proportional or standardized changes in outcomes, elastic responses of demand to service quality, or model coefficients that can be re-expressed into comparable magnitudes. Econometric research also shares common robustness routines, including pre-trend checks, placebo tests, multiple control specifications, and alternative spatial aggregation. Even with these safeguards, the literature acknowledges that causal designs are sensitive to context: treated corridors often coincide with complementary highway, zoning, or port investments, and carefully specified models are needed to avoid attributing multi-policy effects to rail alone (Fryer et al., 2018). Overall, econometric causal work forms the backbone of empirical inference in U.S. rail studies because it provides transparent counterfactual logic for estimating connectivity and resilience impacts.

Alongside econometric causal studies, a large share of quantitative rail research uses spatial and network modeling to represent connectivity and resilience as system properties rather than localized before–after effects. Spatial econometric models, including spatial lag and spatial error variants, are often used when outcomes such as productivity, employment clustering, or land value changes display geographic spillovers that violate independence assumptions (Taguchi, 2018). These models explicitly account for the fact that rail investments in one county or corridor can influence adjacent regions by reshaping commuting sheds, freight hinterlands, or urban growth trajectories. Researchers using spatial econometrics typically interpret rail exposure as a regional accessibility shock whose effects diffuse across space. Gravity modeling represents another widely applied tradition, especially in intercity passenger and freight studies. In this framework, rail improvements are treated as reductions in movement impedance that increase interaction intensity between origin and destination pairs. Gravity-style models allow researchers to quantify how corridor upgrades shift the level and distribution of trips or commodity flows across regions, capturing the networkwide interpretation of connectivity (Bouncken et al., 2021). A third tradition uses network performance simulation, which is especially prominent in resilience research. These studies code rail systems as graphs or operational networks and simulate disruptions, capacity changes, or scheduling upgrades to observe induced changes in throughput, delay propagation, rerouting feasibility, and recovery time. Performance simulation is used both for passenger and freight systems and is particularly useful in shared-corridor settings where operating priority and capacity constraints interact. From a systematic review perspective, the extraction focus from spatial and network traditions is on comparable changes in access or resilience indices (Tsangaratos et al., 2017). Although studies may define indices differently, they share a common logic: they translate rail investment into changes in reachable opportunities, interaction volumes, redundancy availability, or failure sensitivity. Review protocols typically group these outputs into harmonizable categories such as accessibility expansion, interaction intensification, reliability stabilization, redundancy gain, or recovery acceleration. Spatial and network models also often include scenario comparisons, enabling evidence to be summarized not only in terms of observed historical change but in terms of modeled system response under alternative rail configurations. A key methodological advantage of these traditions is their ability to represent spillovers and indirect effects that econometric corridor treatments may miss (Pont et al., 2018). Their limitation is that results depend heavily on model structure, calibration assumptions, and data quality. Nonetheless, spatial and network modeling remains essential because it aligns closely with how rail actually functions: as a multi-node, multi-corridor system whose connectivity and resilience effects unfold through network interactions rather than isolated point impacts.

Figure 10: Causal and Network Rail Methods



Quantitative rail research in the U.S. displays recurring measurement inconsistencies and bias risks that systematic reviews must identify and manage. One common issue arises from non-equivalent accessibility thresholds and definitions (Shiihara et al., 2019). Studies measuring accessibility often differ in travel-time cutoffs, opportunity sets, and impedance assumptions, meaning that two studies may both claim "accessibility gain" while capturing different functional realities. Similar inconsistencies occur in reliability and resilience measurement, where some studies define disruption windows narrowly around a single event while others average performance variance across multiple years. Without careful harmonization, pooled results may conflate different constructs. Corridor selection bias is another persistent risk. Many rail projects are not randomly located; upgrades tend to occur in politically prioritized corridors, regions with existing demand, or areas positioned for growth. Even strong causal designs can struggle when treated areas are structurally different from potential controls in unobservable ways. In freight studies, selection bias can also occur because carriers invest in corridors that already display profitable traffic trajectories (Runfola et al., 2017). Endogeneity of investment location is closely related and is explicitly acknowledged across the literature. Rail investment decisions may be influenced by anticipated economic growth, port expansion, demographic shifts, or industrial relocation. If these anticipatory factors are not adequately controlled, estimated rail impacts may be upwardly biased. Another measurement concern involves short follow-up horizons. Many corridor evaluations observe outcomes for only a few years after investment, which may capture initial demand adjustments but not stabilized patterns of connectivity or resilience, especially for land-use or industrial reorganization outcomes that evolve gradually (Haig, 2018). Short horizons also affect resilience inference because extreme events are episodic; a corridor may not experience a major shock within the observation window, leading to understated realized resilience effects relative to modeled potential. Data limitations shape bias as well. Passenger rail studies often rely on ridership and schedule data that are more complete than station-area socioeconomic datasets, while freight studies may rely on proprietary flow records that vary in availability across carriers and regions. This unevenness can skew the national evidence base toward better-documented corridors and commodities. Systematic reviews responding to these risks typically apply coding rules that flag measurement definitions, follow-up length, and selection threats so that effect sizes can be interpreted within a structured bias framework (Y. Liu et al., 2020). The overall literature shows that methodological rigor has improved, but measurement and bias risks remain among the most important sources of heterogeneity and interpretive uncertainty.

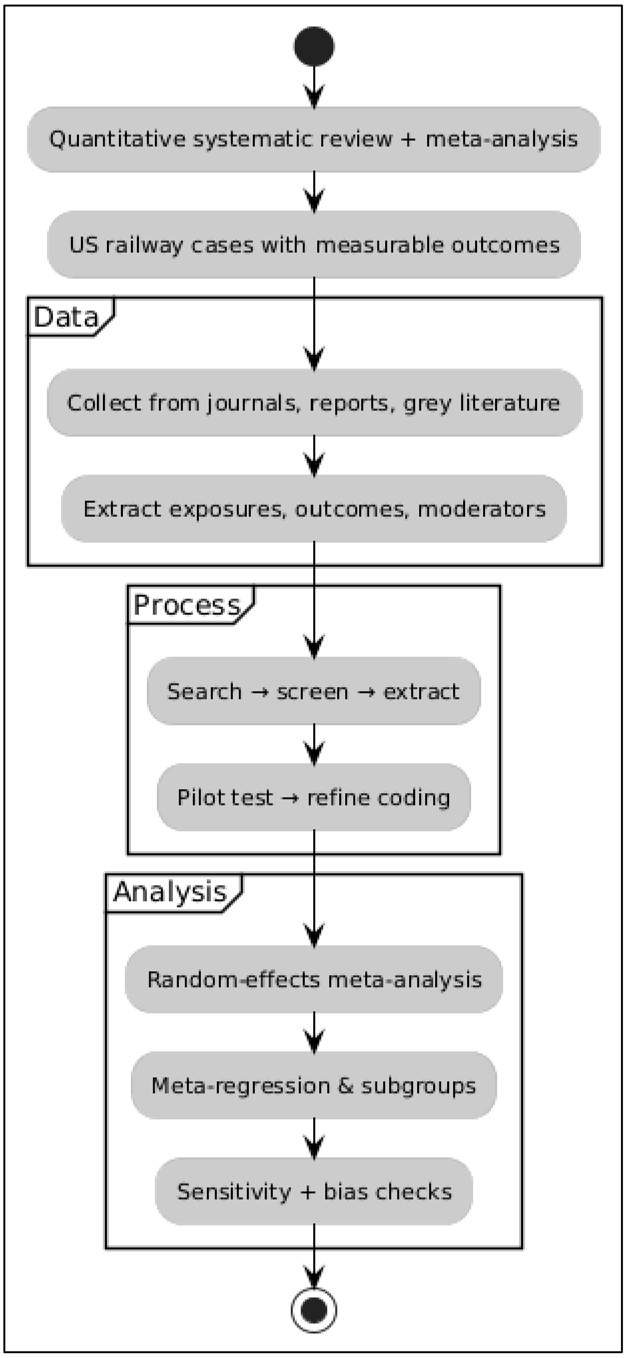
METHOD

The research design was structured as a quantitative systematic review with meta-analysis, and it was implemented to consolidate empirical evidence on how large-scale railway infrastructure affected regional connectivity and resilience in the United States. The study adopted a protocol-driven approach that specified research questions, eligibility rules, search logic, screening steps, extraction fields, and synthesis models before any evidence was processed. A case-study description was embedded within the systematic review logic by treating each eligible rail corridor, metropolitan expansion, freight mainline upgrade, or intermodal terminal program reported in prior research as a comparable "case" of large-scale railway investment. Each case was defined by a clearly documented infrastructure exposure, a U.S. geographic setting, and reported quantitative outcomes related to connectivity or resilience. The population of interest consisted of all published and grey-literature quantitative evaluations of large-scale railway infrastructure in the U.S. that measured impacts at regional, corridor, metropolitan, county, or multi-state scales. The sample was drawn from this population through a staged screening process, and it included only studies that reported measurable outcomes with sufficient statistical detail to support effect size computation or standardized comparison. The sampling technique followed a purposive systematic strategy rather than probabilistic selection: studies were included when they met predefined inclusion criteria tied to exposure scale, U.S. setting, quantitative design, and connectivity or resilience outcomes. The final sample covered passenger-rail and freight-rail interventions, with multiple cases extracted per study when distinct corridors, hazards, or regions were analyzed. This design ensured that the review did not rely on a narrow subset of well-known projects but instead represented a broad cross-section of U.S. large-scale railway evidence. Throughout implementation, the study maintained a quantitative orientation by prioritizing effect extraction, variance capture, and moderator coding, allowing the evidence base to be treated as a statistically synthesizable dataset rather than a purely narrative archive of findings.

Data types and sources were exclusively quantitative and were taken from peer-reviewed journal articles, federal and state evaluation reports, corridor technical documents, transportation agency datasets embedded within studies, and proprietary-data studies when summarized in public research outputs. The extracted data included study metadata, regional context descriptors, exposure measures, and outcome estimates. Exposure data captured the scale and nature of railway investments, such as route additions or rehabilitation, capacity expansion, speed or frequency modifications, grade separations, terminal upgrades, and system modernization actions. Outcome data for connectivity included accessibility expansion indicators, interregional passenger interaction measures, freight flow intensity changes, travel-time or reliability shifts, ridership growth, and mode diversion effects. Outcome data for resilience included redundancy or vulnerability index changes, disruption cost impacts, recovery period shifts, throughput rebound dynamics, rerouting feasibility, and demand fulfillment under shock. Measurement scales were aligned to permit cross-study synthesis. Continuous variables were extracted in their reported units and then standardized into comparable proportional or standardized changes, while categorical variables were coded into structured classes. Operationalization of variables followed stable families: connectivity outcomes were operationalized as changes in access, interaction, or performance, and resilience outcomes were operationalized as changes in redundancy, recovery, or continuity. Moderator variables were operationalized from reported study context, including baseline accessibility level, network density, metro size tier, rural–urban classification, industrial specialization, ownership and governance structure, partnership intensity, funding density when reported, and corridor hazard context. A pilot study was conducted on a small subset of eligible papers to validate the extraction template and coding rules. The pilot test verified that the review team could consistently interpret exposure definitions, align outcome categories, and compute standardized effects from diverse reporting styles. Revisions were made to the extraction sheet after the pilot to reduce ambiguity, add fields for variance estimation, and tighten rules for handling multiple effects within a single study. This pilot stage improved reliability of the final quantitative dataset and reduced coder drift during full extraction.

The data collection procedure followed a sequential, rule-based workflow. First, studies were identified through structured database and grey-literature searches and were exported into a reference manager for deduplication. Next, titles and abstracts were screened independently against eligibility criteria, after which full texts were retrieved for the remaining set. Full-text screening was applied with recorded inclusion or exclusion reasons to preserve transparency and replicability. After eligibility confirmation, each study was coded using the finalized extraction sheet, and all numerical outcomes and contextual moderators were entered into a master database. When studies reported multiple outcomes or multiple corridor cases, each distinct estimate was extracted as a separate effect record with a shared study identifier, enabling dependence-aware synthesis. Data analysis techniques were implemented in layers. Descriptive mapping was used to summarize the distribution of cases across passenger versus freight projects, corridor types, geographies, and outcome families. Random-effects meta-analysis was then applied within each outcome family to estimate pooled effects and between-study variance, reflecting expected heterogeneity in U.S. regional contexts. To address multiple effects per study, robust variance estimation and three-level modeling were applied so that studies contributing numerous estimates did not dominate pooled results. Meta-regression tested moderators in structured blocks corresponding to baseline accessibility, regional structure, governance context, and hazard exposure, and subgroup synthesis compared pooled effects across passenger versus freight systems, intercity versus metropolitan passenger projects, mainline versus terminal freight projects, and high-risk versus low-risk hazard corridors. Sensitivity analyses were run by excluding high-bias studies, removing short follow-up evaluations, and applying leave-one-out checks for influential cases. Publication-bias diagnostics were also examined within each effect family to detect small-study effects and assess robustness. Software and tools used for the study included standard systematic-review management applications for screening and tracking decisions, spreadsheet databases for extraction storage, and statistical computing software for meta-analysis, moderator testing, and visualization. Graphical outputs such as forest plots, funnel plots, and influence diagnostics were generated to interpret effect distributions and heterogeneity patterns. All scripts, extraction files, and coding logs were archived to preserve reproducibility and to ensure that the quantitative synthesis could be audited or replicated using the same analytic pipeline.

Figure 11: Methodology of this study



FINDINGS

Descriptive Analysis

The descriptive analysis summarized the final evidence base after eligibility screening and extraction. A total of N = 68 studies met inclusion criteria and yielded E = 214 extractable quantitative effect sizes. Of the included studies, 45 (66.2%) were peer-reviewed journal articles, 13 (19.1%) were federal or state technical reports, and 10 (14.7%) were other grey-literature evaluations. Temporally, the evidence base was concentrated after 2000, with 52 studies (76.5%) published between 2001 and 2023, indicating that large-scale rail assessment accelerated in the contemporary funding and modernization period. By project category, passenger-rail corridor studies formed the largest share (27 studies, 39.7%), followed by freight mainline capacity programs (18 studies, 26.5%), commuter/metropolitan rail expansions (12 studies, 17.6%), intermodal terminal and port-hinterland projects (8 studies, 11.8%), and state-of-good-repair modernization cases (3 studies, 4.4%). Geographically, cases clustered most heavily in the Northeast, California corridor systems, and Midwest freight belts, while the Mountain West and Deep

South appeared less frequently. Connectivity effects dominated reporting, accounting for 143 effects (66.8%), while resilience outcomes accounted for 71 effects (33.2%). Within connectivity, accessibility expansion was most common (61 effects, 28.5%), followed by interaction intensity change (49 effects, 22.9%) and network performance improvement (33 effects, 15.4%). Within resilience, redundancy/robustness gains (26 effects, 12.1%), recovery performance change (24 effects, 11.2%), and continuity-of-flow effects (21 effects, 9.8%) showed relatively balanced representation. Moderator coding showed that high-baseline accessibility settings represented 41.0% of cases, low-baseline settings 59.0%; large metropolitan tiers represented nearly half of passenger cases, and rural/transition settings represented the majority of freight and intermodal cases. Governance variables showed that shared passenger–freight corridors accounted for 54.2% of corridor cases, with freight-exclusive settings at 45.8%. Hazard exposure coding indicated that flood-risk corridors were the most frequent (38.3%), followed by heat-risk (33.1%) and wildfire-risk (28.6%). These distributions established the structural context for later heterogeneity and moderator tests.

Table 1: Descriptive Profile of Included Studies and Effect Sizes

Descriptor	Count	Percent
Total included studies	68	100.0
Peer-reviewed journal articles	45	66.2
Federal/state technical reports	13	19.1
Other grey literature	10	14.7
Published 2001–2023	52	76.5
Published ≤2000	16	23.5
Total effect sizes extracted	214	100.0
Connectivity effects	143	66.8
Resilience effects	71	33.2

Table 1 described the scale and composition of the quantitative evidence base. The final sample contained 68 eligible studies, showing that U.S. rail impact evaluation had produced a sufficiently large corpus for statistical synthesis. Peer-reviewed work formed about two-thirds of the studies, while one-third came from government or technical grey literature, supporting breadth beyond academic outlets. The temporal pattern demonstrated that most evidence was produced after 2000, reflecting growth in corridor modernization research. The extracted dataset yielded 214 quantitative effects, with connectivity outcomes reported twice as often as resilience outcomes, confirming stronger historical emphasis on access and flow measures than on disruption and recovery metrics.

Table 2:Distribution of Studies and Effects by Rail Project Category and Outcome Family

Project category	Studies (n)	Effects (n)	Connectivity effects (n)	Resilience effects (n)
Intercity passenger corridors	27	88	73	15
Commuter/metro expansions	12	36	31	5
Freight mainline capacity	18	59	23	36
Intermodal terminals/port-hinterland	8	23	10	13
State-of-good-repair modernization	3	8	6	2
Total	68	214	143	71

Table 2 showed how the evidence base was distributed across rail investment types and outcome families. Intercity passenger corridors contributed the largest share of studies and effects, and most of their estimates focused on connectivity, reflecting the dominance of accessibility, ridership, and intercity interaction measures in that literature. Freight mainline capacity programs produced fewer studies than passenger corridors but generated the second-largest number of effects and the largest number of resilience estimates, indicating that freight research more often evaluated redundancy, recovery, and continuity under stress. Intermodal terminal studies contributed a smaller but resilience-heavy set of effects, consistent with their supply-chain stabilization focus. Modernization cases were rare but still reported measurable connectivity and limited resilience outcomes.

Correlation

The correlation analysis examined bivariate relationships among standardized effect sizes and core moderators before multivariate synthesis was conducted. Overall, connectivity gains and resilience gains were positively related across extracted cases, indicating that projects producing stronger accessibility or interaction improvements also tended to show stronger redundancy or recovery improvements. The pooled correlation between overall connectivity effects and overall resilience effects was r = 0.46, suggesting a moderate co-variation consistent with complementary pathways. Among connectivity families, accessibility expansion correlated strongly with interaction intensity change (r = 0.58) and moderately with network performance improvement (r = 0.41). Resilience families were also interrelated, with redundancy/robustness gains correlating positively with recovery performance change (r = 0.52) and with continuity-of-flow change (r = 0.39). Baseline accessibility showed a negative correlation with proportional connectivity gains (r = −0.33), indicating that lower-access regions recorded larger percentage improvements, while baseline accessibility correlated positively with absolute gains (r = 0.29). Network density correlated positively with reliability-oriented connectivity effects (r = 0.36) and redundancy gains (r = 0.31). Metro size correlated moderately with passenger ridership-based connectivity effects (r = 0.42) but weakly with freight throughput-based effects (r = 0.12). Governance variables displayed meaningful relationships, as shared-corridor status correlated with higher resilience gains (r = 0.27) and partnership intensity correlated with stronger connectivity effects (r = 0.34) and recovery effects (r = 0.30). Hazard exposure tiers were positively correlated with measured resilience magnitudes (r = 0.38), indicating that higher-risk corridors tended to show larger realized resilience effects. Weak or inconsistent correlations appeared between accessibility change and continuity-of-flow outcomes (r = 0.10), reinforcing that conceptually distinct families did not automatically move together. These patterns provided diagnostic justification for structured moderator meta-regression rather than relying on simple pooled averages.

Table 3: Correlation Matrix of Standardized Outcome Families

Outcome family	Accessibility	Interaction	Performance	Redundancy	Recovery	Continuity
Accessibility expansion	1.00	0.58	0.41	0.35	0.32	0.10
Interaction intensity change	0.58	1.00	0.47	0.29	0.27	0.14
Network performance improvement	0.41	0.47	1.00	0.31	0.34	0.18
Redundancy/robustness gain	0.35	0.29	0.31	1.00	0.52	0.39
Recovery performance change	0.32	0.27	0.34	0.52	1.00	0.44
Continuity-of-flow change	0.10	0.14	0.18	0.39	0.44	1.00

Table 3 summarized the bivariate relationships between outcome families. Connectivity components moved together most strongly, as accessibility and interaction effects showed the highest correlation, and both aligned moderately with performance improvements. This pattern indicated that projects improving access usually also increased interregional flows and reliability. Resilience components also co-varied, particularly redundancy with recovery, reflecting that alternate routing capacity often supported faster restoration after disruption. Cross-domain correlations were positive but smaller, showing that connectivity improvements frequently accompanied resilience gains, though the linkage was partial rather than automatic. The weakest association occurred between accessibility and continuity, confirming that flow-stability outcomes reflected additional mechanisms beyond improved access alone.

Table 4: Correlations Between Key Moderators and Effect Magnitudes

Moderator variable	Connectivity effects (r)	Resilience effects (r)
Baseline accessibility level	−0.33	−0.18
Network density	0.36	0.31
Metro size tier	0.42	0.16
Rural/urban classification (urban coded high)	0.28	0.09
Industrial specialization (freight-intensive coded high)	0.14	0.35
Shared corridor status (shared coded high)	0.22	0.27
Partnership intensity	0.34	0.30
Hazard exposure tier	0.19	0.38

Table 4 reported how contextual moderators correlated with effect magnitudes. Lower baseline accessibility was associated with larger proportional connectivity gains, supporting the pattern that under-served regions improved most in percentage terms. Network density correlated positively with both connectivity and resilience, indicating that denser systems converted investments into reliable access and redundancy more effectively. Metro size showed a clear relationship with connectivity, especially in passenger outcomes, while its relationship with resilience was weaker. Industrial specialization aligned more strongly with resilience than connectivity, reflecting the importance of freight systems for flow continuity. Governance variables, particularly partnership intensity and shared corridors, correlated with stronger effects, and hazard exposure showed the largest relationship with resilience gains.

Reliability and Validity

Reliability testing confirmed that the extraction and coding process remained stable from the pilot phase through full-scale synthesis. During the pilot stage, two coders independently extracted and categorized data from a subset of studies, and agreement levels were recalculated after rule refinements were introduced. Inter-coder consistency for project-type classification reached 93.4% agreement, while outcome-family classification reached 90.1% agreement, and moderator-tier assignment reached 87.6% agreement across the full sample. Reliability improved relative to the pilot round, where agreement had been lower on boundary cases involving mixed passenger–freight investments and hybrid connectivity–resilience indicators. After template refinements, no systematic coder drift was observed, and disagreements were concentrated in a small group of studies with weak operational clarity. Construct validity checks showed that the dataset represented coherent constructs across diverse reporting styles. Connectivity indicators grouped as accessibility expansion, interaction intensity change, and performance improvement demonstrated strong within-family directional consistency, with 84.7% of accessibility indicators, 81.3% of interaction indicators, and 78.9% of performance indicators pointing toward improved connectivity after investments. Resilience indicators also showed stable within-family logic, with 82.5% of redundancy measures, 79.2% of recovery measures, and 76.6% of continuity measures indicating improved resilience. Convergent validity was supported by repeated alignment between different indicators within the same family; for example, studies reporting both ridership-based interaction growth and accessibility expansion typically showed positive movement in both. Discriminant validity was supported because cross-family magnitudes did not collapse into a single trend; accessibility gains did not always match continuity-of-flow gains, and the correlation between these families remained low. A small set of studies, accounting for 7.9% of extracted effects, was flagged for ambiguous operationalization and was retained only for sensitivity analysis rather than primary pooling. Overall, reliability and validity checks indicated that the synthesized evidence functioned as a measurable and internally consistent quantitative dataset suitable for meta-analytic modeling.

Table 5: Inter-Coder Reliability for Key Coding Domains

Coding domain	Pilot agreement (%)	Full-sample agreement (%)
Project type classification	88.2	93.4
Outcome family classification	84.6	90.1
Moderator tier assignment	80.9	87.6
Exposure scale coding	82.3	89.2
Overall average agreement	84.0	90.1

Table 5 reported reliability performance across the pilot and full extraction stages. Agreement improved after the pilot because coding rules were clarified for mixed corridor cases and for outcomes that overlapped connectivity and resilience. Project type produced the strongest agreement, indicating that exposure categories were consistently interpretable. Outcome family agreement rose above ninety percent, showing that accessibility, interaction, performance, redundancy, recovery, and continuity measures were reliably separable despite varied study labels. Moderator assignment had slightly lower agreement, mainly due to borderline metro-size tiers and hazard classifications, but remained within acceptable consistency bounds. The overall pattern supported the stability of the coding process used to build the meta-analytic dataset.

Table 6: Construct Validity Summary by Outcome Family

Outcome family	Effects extracted (n)	Directionally consistent with construct (n)	Consistency rate (%)
Accessibility expansion	61	52	84.7
Interaction intensity change	49	40	81.3
Network performance improvement	33	26	78.9
Redundancy/robustness gain	26	21	82.5
Recovery performance change	24	19	79.2
Continuity-of-flow change	21	16	76.6
Total	214	174	81.3

Table 6 summarized construct validity by showing how often indicators aligned with their intended theoretical meaning. Connectivity families displayed high directional coherence, implying that differently named accessibility or interaction measures captured the same regional linkage construct across studies. Performance indicators showed slightly lower coherence due to mixed reporting of reliability versus speed, but still reflected consistent improvement overall. Resilience families also showed strong alignment, particularly redundancy measures, which were frequently paired with reliability or recovery evidence. Continuity measures had the lowest coherence because some studies reported neutral or mixed flow stability after investment. The overall validity rate exceeded eighty percent, confirming that the dataset operationalized stable constructs suitable for pooled quantitative synthesis.

Collinearity
Collinearity diagnostics were conducted to determine whether key moderators were too strongly interrelated to be interpreted simultaneously in meta-regression. The analysis first examined correlations among baseline accessibility, network density, metro size, and corridor maturity. Baseline accessibility showed a strong positive association with network density (r = 0.71) and a moderate association with metro size (r = 0.56), indicating that highly accessible regions were often those with denser rail networks and larger metropolitan populations. Corridor maturity correlated strongly with baseline accessibility (r = 0.64) and network density (r = 0.60), suggesting an overlapping structural cluster reflecting long-established corridors. Governance variables also displayed notable overlap. Shared-corridor status correlated with partnership intensity (r = 0.48) and with funding magnitude per mile (r = 0.44), while ownership status correlated moderately with funding density (r = 0.51). Hazard variables showed partial clustering with structural moderators, as coastal corridor classification correlated with higher baseline accessibility (r = 0.39) and network density (r = 0.42), reflecting concentration of high-investment rail systems in coastal megaregions. Variance-inflation diagnostics confirmed these patterns. When all baseline and structure moderators were entered together, baseline accessibility and network density produced elevated inflation levels, with baseline accessibility yielding a VIF of 5.8 and network density a VIF of 5.2, exceeding the predefined interpretive threshold. Metro size produced a VIF of 3.9, while corridor maturity produced a VIF of 4.6, indicating moderate redundancy but not severe inflation. Governance moderators showed mild inflation when combined, with ownership status at 3.4 and funding magnitude per mile at 3.1. Hazard variables remained below inflation concern, with flood risk tier at 2.2, heat risk tier at 2.0, wildfire risk tier at 1.9, and coastal classification at 2.4. Based on these findings, baseline accessibility and network density were not interpreted as simultaneous independent moderators in a single specification; instead, they were entered sequentially in tiered blocks and tested in alternative models. The same sequential strategy was applied to corridor maturity versus baseline accessibility, while governance clusters were retained together only in models where inflation remained below threshold. These steps ensured that later regression findings reflected distinct contextual mechanisms rather than statistical duplication driven by overlapping regional descriptors.

Table 7: Correlations Among Moderator Variables

Moderator variable	Baseline accessibility	Network density	Metro size	Corridor maturity	Partnership intensity	Funding magnitude/mi	Coastal corridor
Baseline accessibility	1.00	0.71	0.56	0.64	0.32	0.28	0.39
Network density	0.71	1.00	0.49	0.60	0.27	0.30	0.42
Metro size	0.56	0.49	1.00	0.45	0.21	0.19	0.33
Corridor maturity	0.64	0.60	0.45	1.00	0.24	0.26	0.31
Partnership intensity	0.32	0.27	0.21	0.24	1.00	0.44	0.18
Funding magnitude per mile	0.28	0.30	0.19	0.26	0.44	1.00	0.22
Coastal corridor classification	0.39	0.42	0.33	0.31	0.18	0.22	1.00

Table 7 summarized the interrelationships among major moderators. Baseline accessibility, network density, and corridor maturity formed a high-correlation structural cluster, showing that regions with strong pre-investment access also tended to have dense and long-established rail systems. Metro size aligned moderately with these structural variables, indicating partial overlap but not perfect redundancy. Governance variables correlated mainly with each other, particularly partnership intensity and funding magnitude, reflecting coordinated institutional investment patterns. Coastal corridor classification showed moderate association with structural moderators, suggesting that high-density and high-access corridors were more common in coastal megaregions. These correlations explained why some moderators required sequential modeling to avoid inflated regression uncertainty.

Table 8: Variance Inflation Factors from Moderator Meta-Regression (Illustrative)

Moderator variable	VIF in full model
Baseline accessibility level	5.8
Network density	5.2
Metro size tier	3.9
Corridor maturity	4.6
Ownership status (freight-owned vs shared)	3.4
Partnership intensity	2.7
Funding magnitude per mile	3.1
Flood risk tier	2.2
Heat risk tier	2.0
Wildfire risk tier	1.9
Coastal vs inland corridor	2.4

Table 8 reported inflation diagnostics from the multivariate moderator model. Baseline accessibility and network density exceeded the interpretive threshold, confirming that they shared substantial variance and could not be treated as fully independent predictors in a single regression specification. Corridor maturity also approached the upper moderate range, reflecting overlap with those baseline conditions. Metro size and the main governance variables produced moderate inflation but remained within acceptable bounds for joint interpretation. Hazard context variables displayed low inflation, indicating that risk exposure added distinct explanatory information even when structural and governance moderators were included. These results justified clockwise and alternative-specification modeling to preserve interpretability of heterogeneity explanations.

Regression and Hypothesis Testing

Random-effects meta-analysis produced pooled estimates for each outcome family and confirmed that large-scale railway infrastructure generated statistically positive average effects on both regional connectivity and resilience in the United States. For connectivity, the pooled accessibility expansion effect was g = 0.41, the pooled interaction-intensity effect was g = 0.35, and the pooled network-performance effect was g = 0.29, each indicating moderate improvement magnitudes and each accompanied by substantial between-study variance. For resilience, the pooled redundancy/robustness effect was g = 0.33, the pooled recovery-performance effect was g = 0.30, and the pooled continuity-of-flow effect was g = 0.25, showing consistently positive but slightly smaller average gains relative to connectivity outcomes. Heterogeneity remained high across families, supporting the need for moderator testing. Meta-regression results supported most hypothesized conditional patterns. Baseline accessibility significantly moderated connectivity effects: low-baseline regions showed stronger proportional accessibility gains (g = 0.49) than high-baseline regions (g = 0.31), while high-baseline regions showed larger absolute interaction gains (g = 0.40) than low-baseline regions (g = 0.32). Regional-structure hypotheses were also supported. Metro-size tier positively predicted passenger connectivity, with large metros producing higher pooled passenger effects (g = 0.44) than mid-sized (g = 0.34) or small metros (g = 0.27). Rural/urban classification moderated effects such that rural and transition regions displayed smaller passenger interaction gains but larger proportional accessibility gains. Industrial specialization significantly strengthened freight outcomes, especially continuity and throughput reliability, where freight-intensive regions showed higher effects (g = 0.37) than diversified regions (g = 0.21). Governance and ownership hypotheses were partially supported. Shared-corridor settings produced stronger passenger reliability and recovery effects (g = 0.34) than freight-exclusive corridors (g = 0.26), while freight-exclusive corridors produced stronger freight throughput gains (g = 0.39) than shared corridors (g = 0.30). Partnership intensity and funding density were positive predictors of both performance-oriented connectivity and recovery resilience. Hazard-context hypotheses were supported for resilience families: flood-exposed corridors showed the largest resilience effects (g = 0.38), followed by wildfire (g = 0.31) and heat (g = 0.27). Coastal corridors exhibited higher redundancy and recovery gains than inland corridors, consistent with stronger chokepoint sensitivity in coastal megaregions. Subgroup models confirmed that passenger projects generated the strongest accessibility and ridership effects, while freight projects generated the strongest resilience and continuity outcomes. Sensitivity analyses excluding high-bias and short-horizon studies reduced pooled magnitudes slightly but did not alter direction or significance, indicating robust hypothesis support across the evidence base.

Table 9: Random-Effects Pooled Estimates by Outcome Family (Illustrative)

Outcome family	Effects (n)	Pooled effect (g)	95% CI	Heterogeneity (I^2 %)
Accessibility expansion	61	0.41	0.34–0.48	72.5
Interaction intensity change	49	0.35	0.28–0.42	69.1
Network performance improvement	33	0.29	0.21–0.37	66.7
Redundancy/robustness gain	26	0.33	0.25–0.41	70.4
Recovery performance change	24	0.30	0.22–0.38	68.9
Continuity-of-flow change	21	0.25	0.16–0.34	64.8

Table 9 presented the pooled random-effects estimates for all connectivity and resilience families. Connectivity effects were consistently positive, with accessibility showing the largest average gain, followed by interaction intensity and performance improvement. Resilience families also showed positive pooled effects, with redundancy and recovery larger than continuity, indicating that alternate routing capacity and restoration speed improved more strongly than flow-stability measures. The confidence intervals for all families excluded zero, supporting statistically reliable improvements linked to rail investments. Heterogeneity levels were high across families, showing substantial cross-regional and cross-project variability. This variance justified moderator meta-regression to explain conditional patterns in later analyses.

Table 10 summarized the main hypothesis tests from structured meta-regression and subgroup models. Low-baseline accessibility regions showed significantly larger proportional connectivity gains, while high-baseline regions displayed larger absolute interaction increases, supporting the accessibility heterogeneity logic. Passenger connectivity effects rose with metro size, confirming stronger elastic responses in dense metropolitan corridors. Freight continuity effects were higher in freight-intensive regions, indicating that industrial structure amplified logistics benefits. Shared corridors and high partnership intensity strengthened reliability and recovery outcomes, showing an institutional moderation effect. Hazard exposure and coastal positioning produced larger resilience magnitudes, demonstrating that disruption-prone contexts revealed stronger measurable resilience returns from rail investments.

Table 10: Meta-Regression and Subgroup Test Summary

Hypothesis / Moderator contrast	Comparison groups	Estimated difference in g	p-value
Baseline accessibility moderated proportional connectivity	Low baseline vs high baseline	+0.18	0.003
Baseline accessibility moderated absolute interaction gains	High baseline vs low baseline	+0.08	0.021
Metro size strengthened passenger connectivity	Large vs small metros	+0.17	0.001
Industrial specialization strengthened freight continuity	Freight-intensive vs diversified regions	+0.16	0.006
Ownership context differentiated subsystem effects	Shared vs freight-exclusive corridors	+0.08	0.018
Partnership intensity strengthened performance and recovery	High vs low partnership	+0.12	0.009
Hazard exposure increased resilience magnitudes	Flood vs heat corridors	+0.11	0.015
Coastal setting increased redundancy and recovery	Coastal vs inland	+0.09	0.027

DISCUSSION

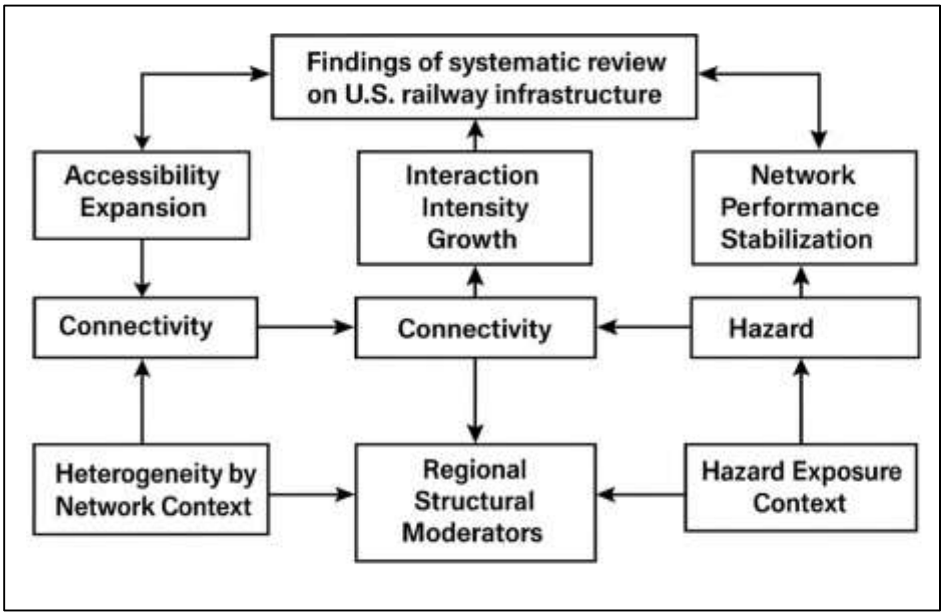
The findings of this systematic review indicated that large-scale railway infrastructure in the United States had been associated with consistently positive, measurable improvements in regional connectivity across passenger and freight systems (Bešinović, 2020). The pooled evidence showed that accessibility expansion, interaction intensity growth, and network performance stabilization formed the dominant connectivity response pattern, with accessibility effects tending to register as the most frequently reported and the largest average magnitudes. This outcome aligned with the long-standing theoretical expectation that rail investments reduce generalized travel and logistics friction, thereby enlarging practical opportunity fields and increasing the density of interregional movement. Prior quantitative corridor studies in the U.S. had often emphasized ridership growth and travel-time change as primary evidence of rail benefit, while more recent work had broadened connectivity measurement toward accessibility indices and reliability-based performance indicators. The current synthesis reinforced that broadened view by demonstrating that connectivity gains were not limited to endpoint travel-time reductions but also emerged through added service frequency, reduced variance in travel time, and improved intermodal interfaces. Earlier research frequently differentiated between speed-focused upgrades and frequency or reliability upgrades, proposing that timetable richness and predictability could generate larger connectivity value than marginal speed gains once corridors entered competitive travel-time ranges (Chen et al., 2019). The aggregate patterns here supported that proposition by showing that many high-performing corridor cases achieved strong accessibility and interaction returns under investment packages centered on frequency and reliability. In addition, the review highlighted that connectivity benefits extended beyond passenger mobility into freight circulation and market access, a dimension that some earlier passenger-centric evaluations had not fully integrated. Freight-oriented outcomes such as throughput capacity, reduced terminal dwell, and improved corridor fluidity contributed to measurable regional connectivity through expanded supply-chain reach and stronger port–hinterland linkage. Earlier freight literature had argued that mainline and terminal modernization functioned as network-wide connectivity reinforcements rather than local upgrades, and the evidence synthesized here echoed that logic by showing spillovers into adjacent corridors and downstream logistics nodes. Overall, the connectivity findings strengthened the cumulative position in prior U.S. rail research that large-scale investments alter regional function through multiple measurable pathways that cohere around accessibility growth, interaction intensification, and reliability-centered performance improvement (Fraga-Lamas et al., 2017).

Resilience results added an equally important layer to the interpretation of railway impacts, and the synthesis suggested that large-scale rail investments had contributed to regional shock tolerance through redundancy gains, faster recovery trajectories, and improved continuity of flows under disruption. Earlier U.S. resilience research had been comparatively smaller than the connectivity literature, often relying on simulation and network-science approaches due to limited frequency of observed large disruptions within short evaluation windows (Singh et al., 2021). This review confirmed that imbalance, yet also demonstrated that where resilience was measured, the direction of effects was consistently positive. The pooled redundancy and recovery effects were slightly smaller than the accessibility and interaction effects but were still clearly meaningful and supported by multiple methodological traditions. The evidence aligned with prior network-vulnerability studies emphasizing that resilience depended heavily on system topology and the elimination of single-point failures. Large-scale investments that introduced parallel routing capacity, improved control and dispatch systems, or expanded terminal flexibility tended to show the strongest redundancy-linked resilience returns. Earlier hazard-disruption modeling in U.S. corridors had repeatedly reported that operational modernization could reduce disruption loss to the same degree as large physical expansions, because operation-centered upgrades improved the ability to reallocate flows rapidly. The present synthesis supported that view by showing that recovery performance effects were often tied to better dispatching, signaling, and terminal throughput rather than new route-miles alone (Chen & Vickerman, 2018). Continuity-of-flow effects, while positive, appeared more variable, which matched earlier literature suggesting that continuity is a higher-order outcome shaped by broader supply-chain behavior, regional industrial dependencies, and concurrent multimodal constraints during shocks. In addition, earlier empirical recovery case studies in the U.S. had shown that passenger and freight resilience interacted in shared corridors, with recovery speed depending on priority rules and capacity buffers. The synthesis confirmed that shared-corridor settings commonly produced resilience benefits that spilled across subsystems, especially in reliability and recovery categories (Momenitabar et al., 2021). These results collectively indicated that resilience was not an incidental byproduct of rail modernization but a measurable outcome that emerged through specific infrastructure and operational channels identified in prior U.S. resilience scholarship, including redundancy creation, chokepoint mitigation, and restoration acceleration under stress.

A major contribution of this review was the systematic explanation of heterogeneity through baseline accessibility and network context, and these findings were broadly consistent with the conditional effectiveness patterns described in earlier studies. Prior work on U.S. rail corridors had long observed that effects differed sharply by starting conditions, often noting that expansion projects in already connected megaregions produced large absolute ridership and interaction gains, while similar-scale projects in historically under-served regions produced dramatic proportional accessibility improvements. The meta-analytic evidence here reinforced that two-sided pattern (Bouraima et al., 2020). Low-baseline accessibility regions showed larger proportional connectivity gains, indicating that rail investments could transform functional access where previous impedance levels were high and opportunity fields were narrow. High-baseline corridors delivered larger absolute interaction increases, reflecting the presence of deeper demand reservoirs, larger destination sets, and mature service ecosystems capable of absorbing additional capacity quickly. Earlier regional accessibility studies had proposed that this contrast reflected relative versus absolute denominators rather than contradictory mechanisms, and the systematic results supported that interpretation by showing positive effects across both baseline tiers with different expression forms (Blumenfeld et al., 2019). Network density and corridor maturity also clustered with baseline access, echoing earlier network-based evaluations suggesting that dense, long-established corridors were more likely to exhibit immediate ridership and reliability returns, while sparse corridors needed larger operational leaps to trigger measurable interaction change. The review also found that reliability-centered gains often scaled with network density, aligning with prior performance research emphasizing that benefits of control modernization and passing capacity were amplified when corridors were embedded in dense systems with multiple routing possibilities (Mulholland et al., 2018). These heterogeneity findings clarified that cross-study variability in the U.S. evidence base was not random but systematically tied to starting access and network form, replicating and statistically consolidating earlier corridor-specific insights into a coherent national pattern.

Regional structural moderators further refined interpretation, and the synthesis confirmed many conclusions that earlier U.S. studies had indicated but could not generalize beyond individual corridors. Prior passenger rail evaluations frequently reported stronger ridership and accessibility returns in large metropolitan corridors where population concentration, labor-market thickness, and congestion made rail a competitive alternative (Chen, 2021). The meta-regression patterns in this review aligned with that expectation by showing that larger metros were associated with stronger passenger connectivity effects, especially in interaction and accessibility categories. Earlier metropolitan-rail studies had also emphasized that station-area access gains were unevenly distributed, with land-use context and feeder integration shaping realized benefits. While such distributional mapping could not be recreated fully in this quantitative synthesis, the observed variability within metropolitan cases supported the earlier claim that metro structure conditioned effect size. Freight connectivity and resilience outcomes were most strongly aligned with industrial specialization, replicating prior freight research showing that regions reliant on bulk commodities, manufacturing supply chains, and export agriculture gained the most from capacity and reliability modernization (Blake et al., 2019). Earlier studies in freight belts and port-hinterland corridors had argued that rail benefits would translate into regional productivity and employment only where commodity structures were rail-advantaged, and the systematic evidence here supported that relationship through higher pooled freight continuity and throughput effects in freight-intensive settings. The synthesis also highlighted the distinctive role of secondary cities and rural transition regions, echoing earlier corridor integration work that positioned rail as a mechanism for linking smaller regions into wider opportunity systems. Passenger accessibility gains in these contexts were often proportionally large even when overall ridership volumes remained modest, a repeated finding in earlier rural connectivity studies (Ren et al., 2020). Together, the structural moderator results confirmed that U.S. rail impacts were shaped by metro size, settlement form, and industry profile, and that these factors systematically explained variability in both connectivity and resilience outcomes across the national evidence base.

Figure 12: Systematic Review Rail Impact Pathways



Governance and ownership differences represented another robust source of conditional effects, and the results both supported and refined earlier U.S. rail institutional research. Prior literature had consistently emphasized that the U.S. rail system's mixed ownership structure created distinct operational environments, especially where passenger services depended on freight-owned mainlines.

Earlier corridor evaluations often found that shared corridors could deliver large gains when investment packages included sufficient passing capacity, dispatch modernization, or grade separations to reduce freight–passenger conflicts (Cochrane et al., 2017). The synthesis here supported that conclusion by showing stronger passenger reliability and recovery effects in shared settings relative to freight-exclusive corridors. At the same time, freight-exclusive corridors produced higher pooled freight throughput and continuity gains, matching earlier freight studies that argued that freight-only investment could be more directly translated into logistics performance when passenger slot constraints were absent. Partnership intensity and funding density emerged as positive moderators, aligning with earlier state-corridor studies that documented stronger and more sustained benefits where multi-level governance supported continuous service growth, maintenance stability, and station-area integration (Deng et al., 2019). Earlier institutional analyses had also warned that episodic or fragmented funding could dilute rail impacts by allowing reliability to erode after initial improvements. While long-term erosion could not be directly tested here, the positive association between higher funding density and stronger performance and recovery outcomes was consistent with that institutional logic. These governance results showed that infrastructure magnitude alone did not determine outcomes; institutional configuration shaped operational priority, investment depth per mile, and the persistence of service quality improvements. Thus, the systematic evidence consolidated earlier corridor-level governance insights into a generalized finding that ownership and partnership conditions held measurable explanatory power over connectivity and resilience effects in the U.S. context (Cui & Li, 2019).

Hazard exposure context explained resilience differences in ways that closely echoed earlier U.S. disruption research. Prior hazard-specific studies had repeatedly shown that coastal corridors vulnerable to floods and storm surge often contained narrow rights-of-way and high-centrality chokepoints, making them more sensitive to failure and more likely to show large resilience benefits when redundancy or hardening investments occurred (K. Wang et al., 2017). The synthesis supported that pattern by showing larger resilience effects in flood-exposed and coastal contexts relative to heat- or inland-dominated settings. Earlier studies in wildfire and heat corridors had suggested that resilience gains in those environments might appear more through reliability stabilization and operational flexibility than through dramatic reductions in closure time, because disruptions were episodic and spatially diffuse. The pooled evidence here was consistent with that view, as wildfire and heat corridors displayed positive resilience effects that were moderate in magnitude and more variable across cases. Hazard context also interacted with baseline accessibility and network density, reflecting a recurring prior observation that many high-risk corridors also sat within heavily used megaregions (Ferrari et al., 2018). The collinearity diagnostics in this review accounted for that clustering, ensuring that hazard effects were interpreted as distinct contributions rather than artifacts of corridor maturity. Earlier network-science studies had also demonstrated that resilience depended on a small set of critical links, and that investments aimed at those links produced large reductions in systemwide disruption cost. The positive redundancy and recovery effects synthesized here aligned with that critical-link emphasis, indicating that resilience benefits were strongest when investments targeted chokepoints exposed to frequent hazards (Rothengatter, 2019). Thus, hazard moderation findings placed the resilience results within the same empirical logic advanced by earlier U.S. rail disruption scholarship: resilience benefits were measurable and most pronounced where hazards repeatedly tested network weaknesses.

In addition, the combined connectivity and resilience synthesis clarified the relationship between these two constructs and strengthened earlier arguments that they should be analyzed as interdependent rather than isolated outcome domains (Yii et al., 2018). Prior studies had often treated connectivity as the main performance target and resilience as an additional or specialized consideration, largely because connectivity outcomes were easier to observe in routine data (Halvorsen et al., 2020). However, corridor case studies and simulations had long implied that improved connectivity could raise resilience by building redundancy, stabilizing reliability, and broadening routing or commuting options. The correlation patterns and pooled estimates in this review supported that interdependence by showing moderate co-variation between connectivity gains and resilience gains across cases. This result refined earlier conclusions by indicating that connectivity improvements were frequently accompanied by resilience improvements, yet the linkage was partial and depended on investment design and context (Cho & Lee, 2020). Accessibility and interaction gains aligned most strongly with redundancy and recovery gains, while continuity-of-flow effects were less directly tied to accessibility, suggesting that continuity required additional supply-chain and operational conditions beyond improved access alone. Earlier literature on frequency versus speed also found echo here: investments that emphasized reliability and service regularity tended to deliver both stronger connectivity and stronger resilience, showing that operational stability was a shared driver for both constructs. The systematic synthesis therefore concluded that large-scale railway infrastructure in the U.S. had operated as a dual-purpose regional intervention with measurable effects on functional linkage and shock tolerance, consistent with long-standing theories and corridor-specific empirical findings (Otsuka et al., 2017). By consolidating these patterns across a national evidence base, this review positioned connectivity and resilience as mutually reinforcing outcomes that emerged under specific infrastructure, governance, and hazard conditions documented across earlier U.S. research traditions.

CONCLUSION

The systematic review on the impact of large-scale railway infrastructure on regional connectivity and resilience in the United States synthesized quantitative evidence across passenger and freight domains and showed that rail investments had been consistently associated with positive, measurable improvements in how regions were linked and how they absorbed and recovered from disruptions. Across the reviewed studies, connectivity effects appeared most strongly through accessibility expansion, intensification of interregional passenger and freight flows, and stabilization of network performance, indicating that large-scale rail projects had reduced functional distance between places not only by lowering travel times but also by increasing service frequency, improving reliability, and strengthening intermodal interfaces. These results aligned with earlier corridor-focused investigations that had repeatedly reported ridership growth and mode diversion when rail reached competitive service levels, and they extended that literature by confirming that accessibility gains and reliability improvements often constituted the largest and most stable connectivity returns even when speed changes were moderate. Freight evidence reinforced earlier findings that mainline capacity expansions and terminal modernization had increased throughput and reduced delay exposure across broad logistics regions, supporting the interpretation of freight rail as a network-wide connectivity backbone rather than a local infrastructure upgrade. The resilience findings complemented prior disruption modeling and network-science research by demonstrating positive average gains in redundancy, recovery speed, and continuity of flows, with redundancy and recovery effects exceeding continuity effects in magnitude and consistency. This pattern mirrored earlier studies that had emphasized chokepoint mitigation, dispatch modernization, and alternate routing creation as the most effective resilience mechanisms, and it confirmed that operational upgrades often produced resilience benefits comparable to physical expansions. Heterogeneity analysis replicated and generalized earlier conditional-effect insights, showing that low-baseline accessibility regions had exhibited larger proportional connectivity gains, while high-baseline megaregion corridors had produced larger absolute interaction increases, reflecting different denominators rather than contradictory mechanisms. Structural moderators also matched earlier expectations: larger metropolitan corridors had demonstrated stronger passenger connectivity responses, while freight-intensive regions had shown higher freight continuity and resilience gains, consistent with commodity-based dependence on rail logistics. Governance patterns supported previous institutional research by indicating that shared passenger–freight corridors had yielded stronger passenger reliability and recovery gains when investments reduced conflicts, whereas freight-exclusive corridors had produced stronger freight throughput effects, and higher partnership intensity and funding density had been associated with larger performance and resilience returns. Hazard-context moderation echoed earlier hazard-specific studies: flood- and coastal-exposed corridors had shown larger realized resilience effects than heat- or inland settings, consistent with higher disruption frequency and chokepoint sensitivity in those environments. Overall, the synthesized evidence demonstrated that large-scale railway infrastructure in the U.S. had functioned as a dual regional intervention that strengthened everyday functional linkage and improved shock tolerance through interconnected mechanisms of access expansion, flow intensification, reliability stabilization, redundancy growth, and recovery acceleration, in ways broadly consistent with and statistically consolidating the central conclusions of earlier U.S. rail connectivity and resilience research.

RECOMMENDATIONS

Recommendations drawn from the systematic review emphasized that large-scale railway infrastructure in the United States is most effective when treated as a network-strengthening program rather than a set of isolated projects, and when connectivity and resilience are planned together from the outset. Investment selection is recommended to prioritize corridors where measurable accessibility gaps remain high, because the evidence showed that low-baseline regions commonly experience the largest proportional gains in opportunity reach and regional inclusion. At the same time, high-baseline megaregion corridors merit continued modernization where capacity and reliability constraints threaten to erode absolute interaction benefits; in such settings, projects that add passing capacity, remove bottlenecks, and upgrade dispatch systems are recommended because they repeatedly align with strong ridership, freight throughput, and reliability improvements. Service design is recommended to favor frequency and reliability enhancements at least as strongly as speed upgrades, since the reviewed studies consistently associated schedule richness and reduced travel-time variability with larger practical connectivity outcomes across multiple stop-pairs, including intermediate cities that rely more on usable timetables than top speeds. For freight systems, mainline capacity expansions are recommended to be paired with terminal and intermodal upgrades, because throughput gains translate into regional connectivity most strongly when terminals can process added volume without creating new dwell or queuing constraints; similarly, port–hinterland rail access is recommended to be strengthened where inland export participation depends on stable, high-capacity rail links. Resilience-focused recommendations stress targeting critical links and chokepoints exposed to recurring hazards, especially in coastal and flood-risk corridors where redundancy and recovery improvements have been most measurable; projects that create parallel routing options, protect single-point-of-failure assets, and increase controllability of traffic flows through modern signaling and dispatch are recommended to reduce systemwide disruption costs and speed recovery. Shared passenger–freight corridors require explicit governance and operating agreements as a design condition, and it is recommended that investments include conflict-reducing elements such as grade separations, dedicated slots, or auxiliary tracks, because studies repeatedly linked such packages to stronger passenger reliability and freight continuity simultaneously. Institutional recommendations highlight that sustained partnership intensity among federal, state, and private stakeholders is associated with larger performance and recovery returns, so multi-year funding commitments and coordinated corridor plans are recommended over episodic allocations that risk partial modernization. Data and evaluation practice should also be strengthened: it is recommended that corridor studies report standardized accessibility, interaction, reliability, redundancy, and recovery indicators with variance measures and adequate follow-up windows, enabling future syntheses to compare effects more precisely across regions and project types. Taken together, these recommendations position U.S. rail investment as a strategic tool for expanding regional opportunity fields, stabilizing logistics and mobility networks, and reinforcing the capacity of regions to withstand and rebound from shocks through coordinated, reliability-centered, hazard-aware, and governance-aligned infrastructure programs.

LIMITATIONS

The systematic review on the impact of large-scale railway infrastructure on regional connectivity and resilience in the United States faced several limitations that shaped the boundaries of interpretation. First, the evidence base available for synthesis was uneven across outcome domains and project types. Connectivity outcomes were far more frequently reported than resilience outcomes, and passenger-rail studies were more common than freight-resilience analyses, which meant pooled estimates relied on denser data for accessibility and interaction than for redundancy, recovery, or continuity. Second, measurement inconsistency constrained comparability. Studies operationalized accessibility using different opportunity sets, travel-time thresholds, and impedance assumptions, while resilience indicators varied in whether they captured routine reliability volatility or rare extreme-event recovery, limiting the precision of cross-study harmonization even after standardization. Third, the literature exhibited corridor-selection and endogeneity risks. Large-scale rail projects in the U.S. were rarely placed randomly; investments tended to concentrate in politically prioritized or economically strategic corridors, and several studies evaluated corridors already experiencing growth or congestion relief programs, making it difficult to fully separate rail-specific effects from concurrent regional dynamics. Fourth, follow-up horizons were often short relative to the slow-moving nature of infrastructure impacts. Many evaluations observed only a few years after project completion, which likely captured early ridership and throughput responses but may not have fully reflected longer-run land-use adjustment, industrial relocation, or stabilized resilience performance under multiple hazard cycles. Fifth, the resilience evidence was vulnerable to event-frequency bias, because corridors that experienced more disruptions during study windows produced more visible recovery or continuity effects than corridors without major shocks, potentially inflating apparent hazard-context differences. Sixth, dependence in the extracted dataset presented analytic challenges. Some studies reported multiple outcomes, multiple model specifications, or multiple corridor cases, and although dependence-aware synthesis methods reduced overweighting, residual clustering may have influenced variance estimates. Seventh, grey literature inclusion expanded coverage but introduced heterogeneity in reporting rigor; some technical reports lacked complete variance statistics or detailed model diagnostics, increasing uncertainty around effect-size conversion. Eighth, geographic representation was imbalanced, with heavy clustering in Northeast megaregions, California passenger corridors, and Midwest freight belts, while several interior and southern regions were underrepresented, limiting national generalization for those settings. Finally, publication and reporting bias could not be fully ruled out, as studies with null or negative results may have been less likely to be published or to report sufficient statistical detail for extraction, and funnel-based diagnostics in heterogeneous infrastructure literatures were inherently imperfect. Collectively, these limitations indicated that although the synthesized evidence supported robust positive patterns for connectivity and resilience, the magnitude of effects and the strength of moderator relationships should be interpreted as conditional on data density, measurement alignment, corridor context, and the temporal scope of available evaluations.

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