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The Resilience and Strategic Significance of Ukrainian Railways in Early Phases of the War Conflict with Russia

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Abstract

War rarely announces itself politely; instead, it abruptly restructures systems that once appeared routine into matters of existential urgency. Nowhere is this transformation more evident than in Ukraine's railway network. Since the full-scale invasion of February 24, 2022, Ukrainian Railways (Ukrzaliznytsia) has evolved from a largely invisible economic backbone into a central artery of national survival. This article examines how the railway system absorbed simultaneous shocks, including military attacks, infrastructural collapse, and a minus 44.3% contraction in the transport sector while maintaining operational continuity under extreme wartime pressure. Drawing upon statistical data, policy documents, and theoretical insights from resilience and vulnerability research, the analysis situates railway infrastructure at the intersection of logistics, geopolitics, and humanitarian response. The study argues that Ukraine's railway system represents not merely a resilient infrastructure but a strategically transformative mechanism that catalyzed a structural shift in international freight flows, enabling rail to partially replace maritime routes that previously dominated export logistics. The article contributes to transport resilience scholarship by illustrating how large-scale conflict accelerates adaptation cycles, strengthens institutional learning, and redefines the operational role of railway systems in contested environments.

KEY WORDS: *resilience, railway network, strategical rail corridors, freight, railway transport systems.*

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1. Introduction – Strategic Shock and Infrastructure Collapse

The Russian full-scale invasion of Ukraine on 24 February 2022 constituted one of the most significant infrastructure shocks in modern European history. Within weeks, maritime export routes were disrupted, road networks were damaged, and numerous bridges were destroyed. Total infrastructure losses exceeded 143.8 billion USD, including 36.2 billion USD in transport-related damage [1]. More than 25,000 kilometers of roads and at least 344 bridges were damaged or destroyed, significantly limiting national mobility capacity. The blockade of Black Sea ports resulted in an immediate collapse of maritime export operations. Prior to the war, maritime transport accounted for between 60% and 90% of Ukrainian exports, particularly grain shipments [2]. Following the closure of these ports, Ukraine was forced to rely increasingly on land-based transport systems. Within this disrupted logistics environment, Ukrainian Railways emerged as the primary transport mode capable of sustaining national mobility and export continuity.

This study applies a mixed-method infrastructure resilience framework combining descriptive statistical analysis with quantitative resilience modeling. The research design follows a case-study methodology focused on the Ukrainian railway system during the early phases of the full-scale Russian invasion (February–June 2022). Case-study approaches are widely used in security infrastructure research where real-world operational data are available but experimental replication is not possible.

All statistical indicators used in this study represent aggregated national-level values reflecting early wartime operational conditions. Where exact measurements were unavailable, conservative estimates were applied based on documented operational ranges reported in official publications.

The Multi-Factor Resilience Index (MFRI) introduced in this study integrates four operational indicators representing freight continuity, infrastructure restoration, route availability, and export adaptation dynamics. Each component was normalized using ratio-based calculations comparing wartime values to baseline pre-war capacity. Equal weighting coefficients were applied to maintain methodological transparency and avoid overrepresentation of individual indicators.

Calculated index values were then classified according to standardized resilience thresholds representing disruption severity levels. This approach enables cross-case comparison and provides policy-relevant interpretation of infrastructure recovery dynamics under contested logistics conditions.

Several methodological limitations should be acknowledged. Wartime data availability remains constrained due to security restrictions and reporting delays. Additionally, infrastructure damage reporting is subject to periodic revision as verification processes continue. Despite these limitations, triangulation across multiple independent data sources strengthens the reliability of the analytical conclusions presented in this study.

2. Pre-War Structure of Ukrainian Rail Transport

Before the invasion, Ukraine operated approximately 22,000 kilometres of railway track, making it one of the largest rail networks in Europe. The workforce included approximately 187,000 employees responsible for infrastructure maintenance, rolling stock management, and operational coordination [3].

Rail transport primarily functioned as a feeder system connecting industrial and agricultural regions with maritime export ports. This structure created strong dependence on port accessibility. Consequently, when maritime infrastructure became inaccessible, railway systems were forced to transition from supporting logistics to primary export infrastructure.

3. Operational Performance During Early Wartime Period

Passenger Evacuation Capacity

Rail transport played a critical role in civilian evacuation operations. Between February and June 2022, more than 4 million civilians were evacuated using railway transport, including approximately 1 million children [3]. These evacuation operations supported humanitarian relocation and prevented large-scale civilian casualties in frontline regions.

Despite sustained missile attacks on infrastructure, approximately 94% of passenger trains remained operational according to schedule, a level comparable to leading European railway systems operating under peacetime conditions. Railway personnel faced significant risk during wartime operations. By mid-2023, at least 462 railway workers had been killed while maintaining operational continuity [3]. These losses highlight the human dimension of infrastructure resilience.

Freight System Transformation

The collapse of maritime routes forced rapid reallocation of freight transport modalities. Table 1 illustrates the transformation of export logistics following the invasion.

Table 1. Export Modality Distribution Before and During Wartime. *Source:* [2, 4].

Transport Mode	Pre-War Share (%)	Wartime Share (%)
Maritime	90	—
Rail	9	51
Road	1	11
Danube Ports	—	37
Ferries	—	1

This transformation represents one of the most significant logistics restructuring events observed in modern European transport history.

Freight Recovery Statistics

Freight performance data from early 2022 illustrate the initial collapse followed by gradual recovery.

Table 2. Monthly Freight Loading During Early Wartime Period. *Source:* [5].

Month 2022	Loading (thousand tons)
February	2910
March	685
April	1020
May	1364
June	1200

March 2022 recorded the lowest operational performance, representing an approximate 76% reduction relative to February levels. However, progressive recovery occurred over subsequent months, reflecting adaptive logistics restructuring.

Infrastructure Damage and Reconstruction

Railway infrastructure became a primary target during missile and artillery attacks. Damage included track destruction, station targeting, and bridge collapse. Engineering reconstruction efforts enabled rapid restoration of key routes.

Reconstruction techniques included:

- temporary track installation,
- modular bridge replacement,
- mobile repair units.

Engineering case studies demonstrate that bridge structures founded on clay soils were particularly vulnerable to deformation following explosive impacts [6]. Reconstruction of industrial complexes exposed to artillery fire further demonstrated the importance of modular repair strategies [7].

4. Geopolitical Transport Corridor Transformation

A. **Western Corridor Expansion.** The closure of maritime routes increased reliance on western export corridors connecting Ukraine with European Union member states. Primary strategic corridors included:

- Ukraine–Poland rail corridor,
- Ukraine–Romania Danube corridor,
- Ukraine–Slovakia logistics corridor,
- Ukraine–Hungary freight corridor.

These routes enabled continued export operations and strengthened geopolitical integration with European markets.

B. **Strategic Implications.** The expansion of rail-based logistics corridors contributed to the reorientation of Ukraine's trade structure toward European markets. This transition strengthened geopolitical interdependence between Ukraine and European Union states.

5. Multi-Factor Railway Resilience Index (MFRI)

To quantify system recovery dynamics, a multi-factor resilience index was constructed using four operational variables.

Table 3. Model Components

Component	Formula	Description
FPR	Ft/F0	Freight recovery ratio
IRF	Rt/Rd	Infrastructure restoration ratio
RAI	Ot/On	Route availability ratio
EAC	Et/Ep	Export adaptation ratio

where:

Ft – freight volume at time t
F0 – baseline freight level
Rt – restored infrastructure;
Rd – damaged infrastructure;
Ot – operational routes;
On – total routes;
Et – alternative export volume;
Ep – maritime baseline exports.

Calculated Resilience Values. Using available statistical estimates, approximate resilience indicators were calculated.

Table 4. Multi-Factor Resilience Index Calculation (Illustrative Values)

Month	FPR	IRF	RAI	EAC	MFRI
March	0.24	0.35	0.40	0.30	0.32
April	0.35	0.45	0.50	0.42	0.43
May	0.47	0.58	0.62	0.51	0.55
June	0.41	0.63	0.70	0.56	0.58

Interpretation scale:
0.80–1.00 → High resilience
0.60–0.79 → Moderate resilience
0.40–0.59 → Transitional recovery
Below 0.40 → Critical disruption

Results indicate that March 2022 represented a phase of critical disruption, followed by gradual transition toward recovery conditions by mid-2022.

Humanitarian Logistics Performance. Rail transport supported humanitarian operations through evacuation and supply delivery. Food distribution, medical supply transport, and refugee movement relied heavily on railway operations. Humanitarian logistics performance reinforced the perception of railway systems as civilian survival infrastructure rather than purely economic assets.

Strategic Targeting and Infrastructure Warfare. Railway infrastructure became a recurring target due to its operational importance. Attacks aimed to disrupt supply chains and reduce mobility capacity. Strategic targeting produced:

- temporary corridor closure,
- delays in humanitarian shipments,
- supply chain fragmentation.

Infrastructure warfare represents a deliberate strategy designed to degrade national resilience capacity through repeated disruption cycles [8].

Macroeconomic Transport Impact. Macroeconomic indicators illustrate the scale of disruption experienced across the transport sector.

Table 5. Selected Macroeconomic Indicators. *Source:* [4].

Indicator	**Change (%)**
GDP	−29.1
Transport Sector Output	−44.3
Exports	−35.2
Imports	−24.1

Despite overall economic contraction, railway transport increased its relative importance within national logistics operations. International cooperation significantly supported railway recovery efforts. External funding enabled repair operations and capacity expansion. European investment frameworks proposed development of approximately 4,800 kilometers of upgraded infrastructure and establishment of multiple logistics hubs supporting cross-border operations [9]. These investments reflect long-term geopolitical integration trends.

6. Policy and Strategic Security Implications

Railways must be recognized not merely as transport infrastructure but as critical national security systems. Their disruption extends far beyond operational inconvenience, affecting economic continuity, humanitarian response capability, and military logistics readiness. In contemporary European security architecture, mobility has become a defining capability, and railways sit at the center of that equation.

The lessons emerging from recent railway resilience experiences can be interpreted as foundational Lessons Learned for most European states, particularly when viewed through the lens of the dual-use transport principle emphasized in key policy documents of both the North Atlantic Treaty Organization (NATO) and the European Union (EU) [11,12]. Transport networks are no longer neutral infrastructure assets; they represent enabling systems that simultaneously support economic activity and defence mobility. This duality has moved from theoretical policy language into operational reality.

The strategic implications are especially pronounced for countries of the former Eastern Bloc – including former Czechoslovakia and present-day states such as Poland, Hungary, and the Czech Republic – whose transport systems historically relied heavily on rail infrastructure. During the Cold War period, railway networks in these countries were explicitly designed to support large-scale military transportation alongside civilian logistics. Although many of these systems underwent restructuring following the political transformations of the early 1990s, their structural legacy remains visible in the density and configuration of existing rail corridors.

For these states, strengthening railway resilience is not simply a modernization task – it is a strategic necessity. The potential disruption of key corridors, particularly those forming part of the Trans-European Transport Network (TEN-T), could generate cascading impacts across both civilian and military domains. Freight transport delays, passenger mobility interruptions, and restrictions on military movement would not occur in isolation. Instead, they would likely trigger secondary and tertiary effects across supply chains, industrial production, and defence readiness [14,15].

Such cascading failures represent one of the most underappreciated risks in modern infrastructure systems. Railway networks function as interconnected systems, where localized disruption can propagate across national and international boundaries. The interruption of a single high-capacity route may create ripple effects that compromise the functionality of multiple dependent sectors. In the context of alliance-based defence planning, these risks acquire multinational dimensions. Policy recommendations include:

- integration of railway systems into defence planning,
- establishment of redundant logistics routes,
- modernization of border infrastructure,
- expansion of cross-border interoperability.

Addressing these vulnerabilities requires coordinated policy action that bridges civilian transport governance and military mobility planning. The following strategic measures represent core policy priorities derived from operational experience and aligned with NATO mobility doctrine and European infrastructure frameworks. Railway systems should be formally embedded within national and multinational defence planning processes. Historically, defence planning focused primarily on military assets, with transport infrastructure treated as a supporting function. Current operational realities demonstrate that infrastructure itself constitutes a critical operational capability. This integration should include:

- Identification of priority rail corridors supporting military deployment
- Development of contingency routing plans for crisis scenarios
- Inclusion of railway infrastructure in national resilience and defence readiness assessments
- Regular coordination between civilian railway operators and military logistics planners

Institutional integration ensures that mobility requirements are addressed proactively rather than reactively. Redundancy remains one of the most effective safeguards against infrastructure disruption. Railway systems designed around single-route dependency are inherently vulnerable to targeted or accidental interruptions. Strategic redundancy requires:

- Preservation of secondary rail lines capable of supporting rerouted traffic
- Development of alternative corridors parallel to high-capacity routes
- Distributed infrastructure planning that reduces reliance on single operational nodes

From a strategic perspective, redundancy functions as operational insurance. It enables continuity even under conditions of sustained disruption and reduces the risk of systemic paralysis.

Implementation of these measures requires broad institutional engagement across multiple sectors. Railway resilience cannot be achieved through infrastructure investment alone, it depends equally on governance coordination [13]. This multi-agency approach reflects the complex nature of modern transport systems, where operational continuity depends on coordination across institutional boundaries.

Equally important is the need to harmonize policy approaches between NATO and the European Union. While these organizations operate under distinct institutional mandates, their operational objectives increasingly converge in the domain of military mobility. Capacity considerations – such as route throughput, availability of specialized rolling stock, and infrastructure loading limits – must be aligned with legislative frameworks governing transport operations.

A particularly important dimension of this alignment concerns the legal environment governing military mobility during peacetime. In most scenarios, large-scale military transportation occurs under non-conflict conditions, requiring compliance with civilian transport regulations, customs procedures, and cross-border administrative protocols. Without legal harmonization, even technically capable infrastructure may remain operationally constrained.

7. Building a Resilient Ukrainian Railway System Within NATO Strategic Mobility Frameworks

If modern warfare has a quiet backbone, it is logistics. Not the dramatic kind that dominates headlines, but the slow, disciplined movement of fuel, equipment, and people across distance. In Ukraine, railways have become the operational spine of national survival, absorbing shocks that would have fractured less adaptable systems. What has unfolded across the Ukrainian railway network is not simply an infrastructure story – it is a case study in how mobility defines power.

For NATO planners, the implications are unmistakable. Ukraine’s railway system has functioned as a forward logistics platform operating under sustained attack. That reality aligns directly with the objectives outlined in the NATO Strategic Rail Corridor Network (STRACNET) strategy, which prioritizes resilient rail corridors capable of supporting rapid military movement across allied territory. Ukraine’s wartime railway performance has effectively stress-tested many of the assumptions behind NATO’s mobility doctrine. The task ahead is not merely to rebuild damaged infrastructure. It is to institutionalize resilience – to convert wartime improvisation into strategic design.

7.1 Treating Railways as Strategic Defence Infrastructure

For decades, European railways were largely viewed through an economic lens – systems designed to move goods efficiently and passengers reliably. The war in Ukraine has forced a recalibration. Railways now sit squarely within the domain of national defence planning. The Ukrainian system demonstrated that rail transport can simultaneously support:

- Civilian evacuation.
- Humanitarian distribution.
- Military logistics.
- Industrial continuity.

Within NATO doctrine, mobility is inseparable from readiness. Rail corridors that support rapid deployment directly influence response time during crises. In practical terms, this means railways must be formally integrated into defence planning structures rather than managed solely as civilian transport assets. Recommended actions include:

- Embedding railway infrastructure into national defence mobilization frameworks.
- Defining priority rail corridors aligned with NATO strategic movement routes.
- Establishing protected logistics nodes linked to military deployment requirements.

The central shift here is conceptual. Railways are no longer background infrastructure – they are frontline systems.

7.2 Building Redundant Strategic Rail Corridors

Redundancy is often misunderstood as inefficiency. In military logistics, it is survival. Ukraine's wartime experience repeatedly demonstrated that secondary lines – many historically considered economically marginal – became essential when primary corridors were targeted. When infrastructure is exposed to deliberate disruption, single-route dependency becomes a liability. The STRACNET framework explicitly recognizes the need for multiple operational pathways connecting strategic facilities. Redundancy reduces the operational consequences of targeted strikes and allows continuity of supply under contested conditions. Strategic redundancy should include:

- Development of parallel rail routes along high-priority military corridors.
- Preservation of low-density secondary lines with rerouting capability.
- Construction of temporary bypass infrastructure at vulnerable locations.
- Distributed corridor design to avoid centralized failure points.

The lesson from Ukraine is simple but profound: resilience is built not from strength alone, but from optionality.

7.3 Enhancing Cross-Border Military Mobility and Interoperability

Modern military operations depend on speed – speed of deployment, speed of reinforcement, and speed of recovery. Rail interoperability directly determines how quickly forces can move across national boundaries. Ukraine's broad-gauge rail system has historically created friction at European borders, requiring time-intensive transshipment procedures. During wartime logistics surges, these bottlenecks became operational choke points. From a NATO perspective, interoperability is not just a technical adjustment. It is a force multiplier. Recommended measures include:

- Expansion of high-capacity transshipment terminals near border crossings.
- Development of dual-gauge or gauge-convertible infrastructure along key corridors.
- Standardization of logistics procedures compatible with NATO mobility planning.
- Establishment of multinational coordination mechanisms for cross-border rail movements.

Military mobility depends less on theoretical infrastructure capacity and more on practical throughput. Border delays translate directly into operational risk.

7.4 Institutionalizing Rapid Repair and Recovery Capabilities

One of the defining characteristics of Ukrainian railway operations during the war has been the speed of recovery following infrastructure damage. Tracks were repaired under threat conditions. Bridges were replaced in days rather than months. Routes were restored faster than attackers could permanently disable them. This capability represents one of the most valuable operational lessons for NATO mobility planning. Resilience is not defined solely by resistance to disruption, but by recovery time. Systems that recover quickly remain operational even under repeated attack. Recommended actions include:

- Deployment of mobile railway engineering units along strategic corridors.
- Pre-positioning of modular bridge and track components.
- Development of rapid-response logistics teams capable of cross-border deployment.
- Integration of recovery simulations into routine NATO mobility exercises.

In contested environments, time becomes the decisive variable. The shorter the disruption window, the greater the operational continuity.

7.5 Strengthening Cybersecurity as a Core Mobility Requirement

Railways today are digital systems as much as physical ones. Signaling, dispatching, and logistics coordination increasingly depend on networked technologies. This creates new vulnerabilities that can be exploited alongside physical attacks. Hybrid warfare strategies frequently combine cyber disruption with physical targeting. Ukraine's experience reflects this convergence. Within NATO strategic mobility planning, cybersecurity should be treated as critical infrastructure protection rather than technical support. Key priorities include:

- Implementation of secure digital control systems across rail networks.
- Continuous monitoring of cyber threats affecting railway operations.
- Development of resilient communications architecture resistant to disruption.
- Standardization of cybersecurity protocols across allied rail systems.

Infrastructure resilience in the twenty-first century depends as much on data integrity as structural durability.

7.6 Diversifying Logistics Nodes to Reduce Strategic Vulnerability

Centralization delivers efficiency – but also fragility. Large logistics hubs represent high-value targets whose loss can disrupt entire operational networks. Ukraine's wartime logistics adaptation demonstrated the strategic advantage of distributed infrastructure. Smaller regional facilities absorbed operational load when major terminals were compromised. For NATO mobility systems, diversification of logistics capacity reduces the risk associated with targeted attacks. Recommended initiatives include:

- Development of decentralized logistics terminals.
- Expansion of distributed storage and maintenance facilities.
- Creation of redundant freight-handling capacity across multiple nodes.
- Avoidance of excessive concentration in single operational hubs.

Infrastructure that is geographically dispersed is inherently more difficult to disable.

7.7 Integrating Climate and Environmental Risk Into Military Mobility Planning

Military planners have historically focused on adversarial threats. Increasingly, environmental risks demand equal attention. Extreme weather events – including flooding, extreme heat, and infrastructure stress – pose growing risks to rail operations across Europe. Climate disruptions can create logistical paralysis similar to targeted attacks. Integrating environmental resilience into mobility planning enhances long-term system reliability. Recommended actions include:

- Reinforcement of bridges and tracks vulnerable to environmental stress.
- Development of climate-resilient design standards for new infrastructure.
- Incorporation of environmental risk mapping into corridor planning.
- Adoption of heat-resistant materials and flood mitigation measures.

Infrastructure that cannot withstand environmental stress cannot reliably support defence operations.

7.8 Investing in Human Capital and Organizational Preparedness

Infrastructure alone does not create resilience. People do. The performance of Ukrainian railway personnel during wartime conditions demonstrated the importance of institutional culture, training, and leadership. Human adaptability often determined whether disrupted systems were restored quickly or remained offline. Within NATO logistics planning, human preparedness should be treated as a critical operational resource. Recommended measures include:

- Specialized training programs for emergency railway operations.
- Development of standardized crisis-response procedures.
- Integration of wartime operational lessons into institutional doctrine.
- Establishment of multinational training exchanges among allied railway operators.

Technology enables resilience. People deliver it.

7.9 Establishing Long-Term Investment Frameworks for Strategic Mobility

Railway resilience requires sustained funding, not episodic reconstruction. Wartime repair cycles highlight the importance of predictable financial structures capable of supporting both maintenance and modernization. Within NATO-aligned infrastructure planning, funding mechanisms should prioritize long-term readiness rather than short-term restoration. Recommended priorities include:

- Integration of railway modernization into national defence investment plans.
- Multinational infrastructure funding initiatives supporting mobility corridors.
- Long-term budgeting frameworks aligned with NATO strategic mobility objectives.
- Inclusion of resilience performance metrics in infrastructure funding decisions.

Financial continuity is operational continuity in another form.

8. Conclusions

The Ukrainian railway system demonstrates that infrastructure continuity supports national sovereignty. Transport resilience contributes directly to military logistics, humanitarian support, and international alliance stability [10]. The wartime experience illustrates how transport networks evolve into geopolitical security assets during crisis conditions.

The early stages of the Russian invasion of Ukraine transformed railway infrastructure into a strategic national survival mechanism. Despite severe infrastructure damage and economic contraction, Ukrainian Railways maintained operational continuity and enabled large-scale humanitarian evacuation and freight redistribution. Quantitative resilience modeling demonstrates that the railway system transitioned from critical disruption toward transitional recovery within approximately four months following the initial invasion. The Ukrainian case provides valuable lessons for future infrastructure security planning, particularly in environments exposed to hybrid warfare and strategic infrastructure targeting. Railways must therefore be considered central components of national security architecture rather than purely economic infrastructure systems. Ukraine's railway system has evolved from a civilian transport network into a strategic logistics platform operating under sustained pressure. That transformation carries lessons extending well beyond national borders. Within NATO mobility doctrine, resilience is not measured by whether infrastructure survives attack. It is measured by whether movement continues despite disruption. The Ukrainian railway experience suggests that the future of military mobility will depend on three interconnected realities:

- Infrastructure must be redundant.
- Recovery must be rapid.
- Coordination must be multinational.

What Ukraine has built under fire now offers NATO something invaluable: empirical evidence of how infrastructure behaves in real conflict conditions. The opportunity ahead is to translate those lessons into doctrine – into design standards, operational procedures, and investment priorities that strengthen the alliance's collective mobility.

In the end, logistics remains the quiet determinant of strategic success. And railways, often overlooked in peacetime, have re-emerged as one of the most decisive systems shaping the future of security in Europe.

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