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Stage-Coupled Failure in Metro Station Emergency Management Under Compound Hazards: Implications for Urban Infrastructure Resilience

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Abstract

Metro station emergencies are increasingly characterized by compound hazards, where multiple disruptions interact across emergency management stages. Existing approaches typically focus on technical failures or isolated stages, overlooking how management processes themselves can generate and amplify system-level risks. This study introduces the concept of stage-coupled failure, which explains how failures propagate across preparedness, response, and recovery through interdependent management mechanisms. A theory-building approach is adopted, combining systematic literature synthesis with scenario-based analysis. Four coupling mechanisms—resource, information, organizational, and temporal—are identified to structure cross-stage interactions. A semi-quantitative representation is further proposed to capture feedback loops and nonlinear dynamics. The findings show that failure escalation is driven by cross-stage interactions rather than isolated breakdowns. The proposed framework provides a new perspective for understanding compound hazard dynamics and supports applications in safety assessment and emergency management planning.

Keywords: stage-coupled failure; compound hazards; emergency management; socio-technical systems; metro stations; safety management

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1. Introduction

1.1. Background

As cities continue to densify and transportation systems become increasingly interdependent, metro systems are required to maintain safe operation under a growing spectrum of disturbances, ranging from technical failures to natural hazards and operational disruptions [1,2]. Within these systems, metro stations represent particularly vulnerable nodes, where physical infrastructure, technical subsystems, organizational processes, and human behavior converge in confined and highly coupled environments (Figure 1) [3,4]. High passenger densities and constrained circulation spaces can further amplify emergent crowd dynamics and cascading service impacts, especially under abnormal conditions [5,6].

Disruptions occurring at the station level rarely remain localized [7,8]. Due to spatial enclosure, high passenger density, and strong functional interdependencies among subsystems such as power supply, ventilation, communication, and signaling, even minor incidents can escalate rapidly into system-wide emergencies [9]. Metro stations exemplify tightly coupled socio-technical systems in which failures propagate through both technical and managerial processes [10].

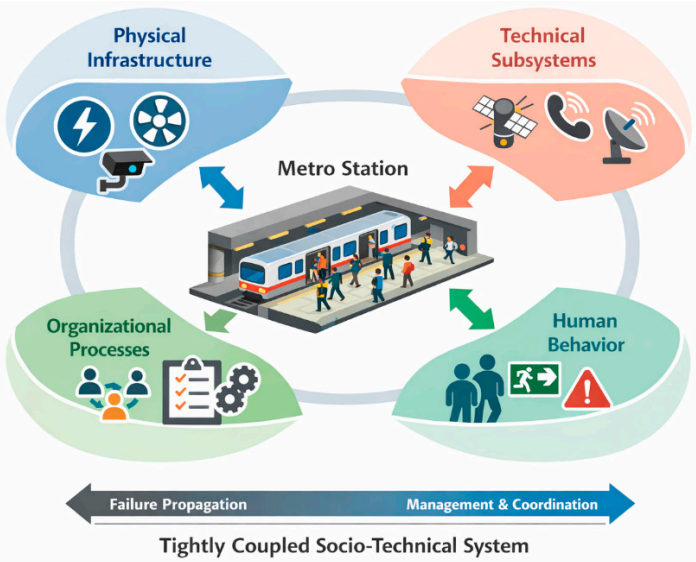


Figure 1. Metro stations as tightly coupled socio-technical systems.

1.2. Problems: Emergency Management Under Compound Hazards

Conventional emergency management frameworks typically conceptualize emergencies as staged processes encompassing preparedness, response, and recovery [11,12]. This staged structure provides analytical clarity and practical guidance for planning, training, and evaluation and has been widely adopted in both research and operational practice [11–13]. However, the increasing complexity of metro systems and the emergence of compound hazards—in which multiple disruptive events occur simultaneously or in close temporal proximity—raise critical questions about the adequacy of stage-separated approaches to emergency management [14,15]. Recent emergency events demonstrate that emergencies in metro stations are increasingly compound in nature. Fires may coincide with power outages, earthquakes may disrupt both physical infrastructure and communication systems, and extreme weather events may simultaneously trigger flooding and abnormal passenger congestion [15,16].

Under such conditions, emergency managers are often required to operate with degraded resources, fragmented information, and unstable organizational coordination [17]. Failures in these events cannot be fully explained by hazard intensity or technical damage alone. Instead, they frequently reflect the amplification of latent managerial and organizational weaknesses embedded in emergency management processes [17,18].

1.3. Research Gap

Despite growing attention to compound hazards and cascading failures in safety science and infrastructure research, existing studies tend to focus on component-level or network-level failure propagation, emphasizing physical interdependencies among technical subsystems [19,20]. In parallel, research on metro station emergency management has largely concentrated on individual emergency stages, particularly evacuation performance during the response phase, often under single-hazard assumptions [21–24]. However, a key question remains insufficiently addressed: Why do emergency management systems that appear well-prepared nevertheless experience escalating failures when confronted with compound hazards?

More specifically, existing research provides limited explanations of how decisions, resource configurations, and organizational arrangements established during preparedness constrain response options, or how response-stage actions shape recovery trajectories in tightly coupled socio-technical environments [17,25]. Consequently, current studies still

lack a systematic explanation of how managerial processes link emergency management stages and shape failure propagation under compound hazard conditions. This gap limits the ability of existing studies to explain failure propagation across emergency management stages under compound hazards.

1.4. Concept of Stage-Coupled Failure

To address this gap, this study advances a process-oriented perspective on emergency management failure, conceptualizing preparedness, response, and recovery not as analytically independent stages but as interdependent managerial processes linked through multiple coupling mechanisms. Stage-coupled failure differs from conventional notions of cascading failure by shifting the analytical focus from physical components to managerial processes and decision-making structures. The framework links resource availability, information flows, organizational coordination, and temporal constraints across emergency stages, creating pathways through which failures propagate and intensify over time. Emergency outcomes are not solely determined by hazard characteristics but emerge from cross-stage interactions within emergency management systems.

While cascading failure analyses focus on how failures propagate across technical components or networks, stage-coupled failure focuses on how managerial decisions and organizational arrangements propagate constraints across emergency management stages. The unit of analysis is not infrastructure components, but emergency management processes.

1.5. Methodological Approach

This study adopts a theory-building research design to develop a conceptual framework explaining stage-coupled failure in metro station emergency management under compound hazards. The methodology integrates qualitative synthesis and mechanism-based analysis to systematically identify and interpret cross-stage failure propagation. The methodological process consists of three main steps.

First, a structured literature review was conducted using the Web of Science and Scopus databases. Keywords such as “metro emergency management”, “compound hazards”, “cascading failure”, and “multi-stage systems” were used to identify relevant studies. The review focused on research addressing emergency processes, interdependencies, and failure propagation mechanisms in complex socio-technical systems.

Second, qualitative coding and thematic analysis were applied to extract recurring patterns from the literature. Through iterative comparison and abstraction, key interdependencies among emergency management stages were identified. These patterns were synthesized into four coupling mechanisms: resource, information, organizational, and temporal coupling.

Third, a scenario-based analytical approach was employed to examine how these coupling mechanisms operate under compound hazard conditions. Rather than reconstructing specific events, representative scenarios were used as analytical archetypes to explore the dynamics of cross-stage interactions. This approach enables a systematic examination of feedback loops and nonlinear propagation processes in emergency management systems.

This method constitutes the methodological foundation of the study, providing a structured basis for the development and validation of the proposed framework. Unlike descriptive reviews of metro emergency systems, this study focuses on explaining how cross-stage interactions generate failure propagation, thereby shifting the emphasis from background description to mechanism-based analysis.

1.6. Objectives and Contributions

This study aims to explain stage-coupled failure in metro station emergency management under compound hazards. This study makes three main contributions:

(1) It introduces the concept of stage-coupled failure, providing a process-oriented perspective to explain how emergency management failures propagate across preparedness, response, and recovery stages under compound hazards.
(2) It identifies four core coupling mechanisms—resource, information, organizational, and temporal coupling—that structure cross-stage dependencies and drive failure amplification in metro station emergency management.
(3) It develops a scenario-based analytical framework to illustrate how compound hazards activate these coupling mechanisms, offering practical insights for improving resilience in tightly coupled socio-technical systems.

2. Conceptual Framework: Stage-Coupled Emergency Management

2.1. Analytical Framework Overview

Emergency management in metro stations is commonly described through a sequence of stages, typically encompassing preparedness, response, and recovery [11]. While this staged representation offers organizational clarity, it risks obscuring the processual and interactive nature of failure propagation in tightly coupled socio-technical systems [26]. In particular, under compound hazard conditions, failures rarely originate and remain confined within a single stage. Instead, they emerge through cross-stage interactions, in which managerial decisions, resource configurations, and organizational arrangements established in one stage constrain and amplify failures in subsequent stages.

The framework is built on two core premises. First, emergency management stages should be understood as interdependent managerial processes, rather than discrete operational phases. Second, failures propagate across stages through identifiable coupling mechanisms that link resources, information, organizational structures, and temporal constraints.

2.2. Interdependence of Emergency Management Stages

2.2.1. Beyond Linear Stages

Traditional emergency management frameworks conceptualize preparedness, response, and recovery as sequential stages aligned with the temporal progression of an emergency event [27]. However, from a safety science perspective, such a linear interpretation is insufficient for understanding failure dynamics in tightly coupled socio-technical systems [28].

In metro stations, preparedness, response, and recovery are not temporally isolated or functionally independent. Decisions made during preparedness—such as resource allocation, redundancy design, training intensity, and coordination protocols—directly shape the operational conditions under which response actions unfold [29]. Similarly, response-stage decisions regarding evacuation, communication, and damage control strongly influence recovery trajectories, including infrastructure restoration, service resumption, and organizational learning [30].

Under compound hazard conditions, these interdependencies become particularly salient [31]. The simultaneity of multiple disruptions compresses decision time, degrades information quality, and strains organizational coordination. Emergency management performance emerges not from the effectiveness of individual stages, but from the quality of interaction among stages.

2.2.2. Role of Preparedness

While preparedness is often evaluated in terms of completeness or compliance, its more fundamental role lies in structuring the conditions under which response and recovery must operate. Preparedness-stage decisions determine the availability, accessibility, and flexibility of critical resources such as trained personnel, emergency equipment, backup power, communication systems, and evacuation infrastructure [32]. They also define organizational architectures, including command hierarchies, role definitions, and communication protocols [33]. These configurations function as boundary conditions for subsequent emergency management stages.

Many preparedness deficiencies remain latent during routine operations. Limited redundancy, insufficient cross-training, or fragile coordination arrangements may not produce observable safety problems under normal conditions [30,34]. However, when compound hazards occur, these latent weaknesses are activated, sharply reducing adaptive capacity and constraining response options. From a stage-coupling perspective, preparedness failures are therefore not merely early-stage problems, but structural vulnerabilities that shape failure propagation across the entire emergency management process.

2.2.3. Response Under Constraints

The response stage involves real-time decision-making, command and control, communication, evacuation management, and coordination among multiple actors operating under time pressure and uncertainty [35,36]. In metro stations, response activities must be conducted in confined spaces, often with high passenger density, limited visibility, and degraded technical systems [37].

Contrary to procedural representations of response as the execution of predefined plans, response in practice constitutes a process of dynamic adaptation under constraints [29]. Frontline staff and managers continuously interpret evolving conditions, adjust priorities, and improvise actions in the face of incomplete information. The effectiveness of such adaptation depends heavily on the resources, information infrastructures, and organizational arrangements inherited from the preparedness stage.

When preparedness is insufficient, response becomes increasingly improvisational. While improvisation may compensate for isolated disruptions, under compound hazard conditions, it often leads to fragmented decision-making, inconsistent actions, and delayed coordination. These response-stage failures, shaped by preparedness-stage constraints, have direct implications for recovery effectiveness and duration.

2.2.4. Recovery Continuity

Recovery is often conceptualized as a post-emergency phase focused on infrastructure repair, service restoration, and the return to normal operations [38,39]. However, in tightly coupled systems such as metro stations, recovery cannot be analytically separated from response [40]. Instead, it represents a continuation of emergency management processes, shaped by earlier decisions and resource trajectories. Response-stage actions—including evacuation timing, damage documentation, information dissemination, and coordination with external agencies—significantly influence recovery planning and execution [41]. Delayed evacuation, incomplete situational records, or organizational fatigue accumulated during response can complicate recovery efforts, prolong service disruption, and increase secondary risks [42]. Moreover, recovery outcomes feed back into future preparedness through organizational learning, policy revision, and system redesign [43]. From a stage-coupled perspective, preparedness, response, and recovery form a recursive and interdependent system, rather than a linear sequence of discrete phases.

2.3. Coupling Mechanisms

The identification of these coupling mechanisms is based on a bottom-up qualitative coding process. Key concepts related to interdependencies across emergency management stages were extracted from the reviewed literature and categorized through iterative coding and thematic analysis.

Through this process, four recurring dimensions of cross-stage dependency were identified: resource-related constraints, information flow disruptions, organizational coordination structures, and temporal dependencies. These dimensions were subsequently conceptualized as resource, information, organizational, and temporal coupling mechanisms.

In tightly coupled systems, failure propagation follows structured dependency pathways rather than random processes [44]. To explain how deficiencies in one emergency stage systematically amplify failures in subsequent stages, this study identifies four primary stage-coupling mechanisms: resource coupling, information coupling, organizational coupling, and temporal coupling. These mechanisms define how preparedness, response, and recovery are interconnected. Under compound hazard conditions, they interact and reinforce one another, transforming localized weaknesses into cascading system-level failures.

2.3.1. Resource Coupling

Resource coupling refers to the dependence of emergency management activities in later stages on resources allocated, configured, or reserved during earlier stages. In metro station emergency management, critical resources include trained personnel, emergency equipment, backup power supply, communication devices, and physical space for evacuation and staging. Preparedness-stage decisions determine not only the quantity of these resources, but also their accessibility, flexibility, and substitutability under degraded conditions. Limited staffing levels, insufficient redundancy in power or ventilation systems, or emergency equipment stored in inaccessible locations may not generate observable problems during routine operations. However, when compound hazards occur and multiple subsystems are simultaneously stressed, these latent constraints become immediately consequential. Resource coupling operates as a failure propagation mechanism when preparedness-stage resource limitations constrain response-stage options. In this condition, emergency managers are forced to rely on ad hoc reallocation or improvisation. While temporary workarounds may mitigate isolated disruptions, compound hazards reduce the effectiveness of improvisation by placing simultaneous demands on multiple resource categories. Resource shortages during response delay evacuation, hinder firefighting or rescue operations, and increase cognitive and physical strain on personnel. These response-stage resource constraints extend into recovery. Prolonged response efforts deplete personnel and equipment, limit repair capacity, and slow the restoration of normal operations. Through resource coupling, therefore, preparedness-stage deficiencies are amplified across stages, transforming initial constraints into prolonged recovery disruption.

2.3.2. Information Coupling

Information coupling captures the dependence of emergency management effectiveness on the continuity and quality of information flows across stages. Effective emergency management relies on timely, accurate, and shared information regarding hazard conditions, system status, passenger behavior, and operational constraints. Preparedness-stage investments in information infrastructure—including communication systems, data integration platforms, and training in information interpretation—directly shape response-stage situational awareness. Under compound hazard conditions, information systems are particularly vulnerable. Power outages, physical damage, network congestion, and organi-

zational overload can simultaneously degrade multiple communication channels. When information flows are disrupted, response-stage decision-making becomes fragmented. Managers may operate with incomplete or outdated situational awareness, leading to delayed decisions, inappropriate prioritization, or misallocation of resources. Frontline staff may receive inconsistent instructions, while coordination with external emergency services becomes increasingly difficult. These information failures are not merely technical breakdowns, but manifestations of information coupling between preparedness and response stages.

Information coupling also extends into recovery. Incomplete damage assessments, inconsistent documentation, and poor information sharing during response complicate recovery planning and inter-agency coordination. Moreover, information gaps hinder post-event learning, limiting the ability of organizations to update preparedness arrangements. Thus, information coupling provides a pathway through which degraded situational awareness propagates across emergency stages, even in the absence of severe physical damage.

2.3.3. Organizational Coupling

Organizational coupling refers to dependencies created by authority structures, role definitions, coordination mechanisms, and inter-organizational relationships that link emergency management stages. In metro stations, emergency management typically involves multiple organizational actors, including station staff, control centers, metro operators, emergency responders, and local authorities. Preparedness-stage organizational design determines how authority and responsibility are distributed during emergencies. Command hierarchies, escalation protocols, and coordination arrangements may function adequately under routine or single-hazard conditions. However, under compound hazards, ambiguities in authority, overlapping responsibilities, or rigid coordination structures can rapidly undermine response effectiveness. Organizational coupling becomes a failure propagation mechanism when such design limitations constrain response-stage coordination. Fragmented authority structures may delay critical decisions, generate conflicting instructions, or lead to duplication of effort. Trust deficits among organizations, often rooted in limited preparedness-stage interaction, further exacerbate coordination breakdowns. These organizational failures frequently persist into recovery. Effective recovery requires sustained coordination across agencies for inspection, repair, service restoration, and public communication. Organizational fragmentation and fatigue accumulated during the response reduce recovery efficiency and prolong the disruption. Through organizational coupling, therefore, managerial and institutional arrangements create durable pathways for cross-stage failure amplification.

2.3.4. Temporal Coupling

Temporal coupling describes how delays or inefficiencies in one emergency management stage compress the available time window for subsequent stages. In emergency contexts, time functions as a critical and non-renewable resource, particularly during evacuation, damage control, and stabilization. Preparedness-stage deficiencies may delay initial mobilization, while response-stage constraints—arising from resource shortages, information loss, or organizational confusion—can significantly slow emergency actions. Under compound hazards, these delays accumulate rapidly as simultaneous disruptions intensify time pressure. Temporal coupling amplifies failure propagation by reducing the flexibility of subsequent stages. Delayed evacuation increases exposure to secondary hazards; prolonged response exhausts personnel and equipment, limiting recovery capacity; compressed recovery timelines increase vulnerability to follow-on incidents. Temporal coupling

interacts with other coupling mechanisms: resource shortages intensify delays, information loss prolongs decision-making, and organizational fragmentation slows coordination.

As a result, early-stage inefficiencies often have disproportionate downstream impacts, explaining why relatively modest initial disruptions can escalate into prolonged system-level failures under compound hazard conditions.

2.3.5. Mechanism Interactions

Although analytically distinct, the four coupling mechanisms rarely operate in isolation. Under compound hazard conditions, they interact and reinforce one another, generating nonlinear failure propagation dynamics. Resource shortages exacerbate information loss; information degradation intensifies organizational fragmentation; organizational breakdowns amplify temporal delays. These interactions increase coupling strength across emergency stages, reducing the system's ability to compartmentalize failures. Understanding stage-coupled failure therefore requires attention not only to individual coupling mechanisms, but also to their combined effects. These interacting couplings explain why emergency management systems that perform adequately under single-hazard or routine conditions may nevertheless experience cascading failures when confronted with compound hazards.

Taken together, these coupling mechanisms do not operate in isolation. Rather, they form an integrated structure that links emergency management stages and shapes how failures propagate across preparedness, response, and recovery, as illustrated in Figure 2. The interactions among coupling mechanisms form feedback loops that can amplify disruptions across stages, leading to nonlinear failure propagation.

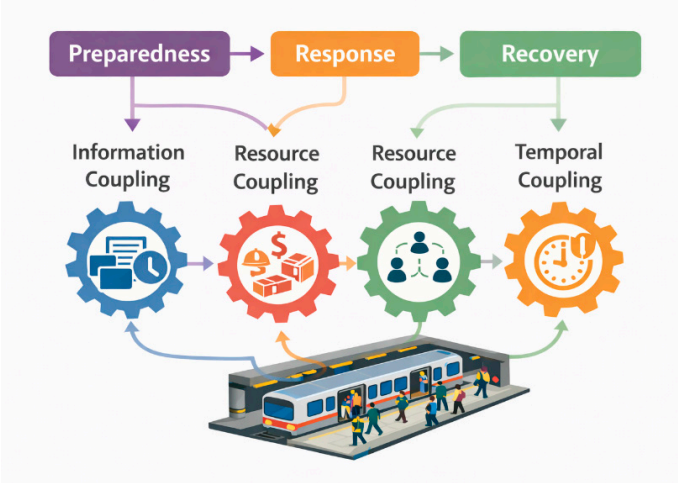


Figure 2. Coupling mechanisms linking emergency management stages in tightly coupled metro stations.

2.4. Stage-Coupled Failure

Building on the preceding analysis, this study conceptualizes stage-coupled failure as a distinct failure mode in emergency management systems operating under compound hazard conditions. Unlike failures that originate from isolated technical breakdowns or hazard severity, stage-coupled failure emerges through systematic interactions among emergency management stages, mediated by managerial and organizational coupling mechanisms.

2.4.1. Definition of Stage-Coupled Failure

In this study, stage-coupled failure is defined as a management-induced failure process in which deficiencies in one emergency management stage systematically constrain and

amplify failures in subsequent stages through resource, information, organizational, and temporal coupling mechanisms, particularly under compound hazard conditions.

This definition emphasizes several critical features. First, stage-coupled failure is processual rather than event-based. It unfolds over time as decisions, constraints, and adaptations interact across preparedness, response, and recovery, rather than manifesting as a single point of breakdown. Second, stage-coupled failure is management-induced, highlighting that failure propagation is driven primarily by managerial decisions, organizational arrangements, and resource configurations, rather than by hazard intensity or physical damage alone. While hazards trigger emergencies, it is the structure of emergency management processes that determines whether disruptions remain contained or escalate. Third, stage-coupled failure is systematic rather than accidental. Failure propagation follows identifiable coupling pathways that link emergency management stages, allowing latent deficiencies to be activated and amplified under compound hazard conditions.

2.4.2. Distinction from Related Failure Concepts

Stage-coupled failure is conceptually related to, but analytically distinct from, several established failure concepts in safety science. Cascading failure research primarily focuses on component-level or network-level interdependencies, explaining how failures propagate through physical or functional connections among technical subsystems. While such analyses are essential for understanding infrastructure vulnerability, they provide limited insight into how managerial processes shape failure dynamics across emergency stages. Similarly, resilience-oriented analyses often evaluate system performance in terms of capacities such as robustness, redundancy, and recovery speed. Although valuable, these approaches tend to assess capacities at specific stages or system levels without explicitly examining how deficiencies in one stage constrain or undermine performance in subsequent stages.

In contrast, stage-coupled failure shifts the unit of analysis from technical components or static capacities to emergency management stages as interdependent managerial processes. It explicitly examines how preparedness structures response conditions, how response actions shape recovery trajectories, and how failures are amplified through cross-stage interactions rather than linear sequences. From a safety science perspective, stage-coupled failure therefore complements existing failure and resilience frameworks by introducing a cross-stage, process-oriented lens that captures managerial pathways of failure propagation in tightly coupled socio-technical systems.

2.4.3. Implications

First, it challenges the implicit assumption that emergency management stages can be optimized independently. Under compound hazards, improvements in one stage may be neutralized—or even counteracted—by deficiencies in others. Safety performance thus emerges from cross-stage coherence, rather than isolated excellence. Second, stage-coupled failure highlights new leverage points for intervention. Rather than focusing exclusively on enhancing individual stage performance, safety interventions can target coupling mechanisms themselves—for example, by increasing resource flexibility, improving information continuity, or designing organizational structures that remain functional under degraded conditions. Third, the concept provides a basis for explaining why emergency management systems that perform adequately under routine or single-hazard conditions may nevertheless experience escalating failures when confronted with compound hazards. By strengthening coupling among stages, compound hazards reduce the system's ability to compartmentalize disturbances, increasing the likelihood of failure amplification. Finally, stage-coupled failure offers a framework for integrating managerial and organizational analysis into safety science research on systemic risk. It demonstrates that cascading failures

in complex socio-technical systems are not solely technical phenomena but often reflect process-level vulnerabilities embedded in management systems.

2.5. Semi-Quantitative Representation of Stage-Coupled Failure

To complement the qualitative analysis, a semi-quantitative representation is introduced to formalize the mechanism of stage-coupled failure. Let the overall emergency management performance be denoted as S, which is influenced by four coupling dimensions: resources (R), information (I), organization (O), and time (T). The system state can be expressed as follows:

$$S = f\ (R, I, O, T) \tag{1}$$

Each variable represents the effectiveness of the corresponding mechanism across emergency management stages. Under compound hazard conditions, deficiencies in one dimension may propagate and amplify across stages through coupling effects. The interaction among these variables can be conceptualized as follows:

$$R\ (t + 1) = R\ (t) - \alpha_1 \cdot \Delta I - \alpha_2 \cdot \Delta O \tag{2}$$

$$I\ (t + 1) = I\ (t) - \beta_1 \cdot \Delta R - \beta_2 \cdot \Delta O \tag{3}$$

$$O\ (t + 1) = O\ (t) - \gamma_1 \cdot \Delta I - \gamma_2 \cdot \Delta T \tag{4}$$

$$T\ (t + 1) = T\ (t) - \delta_1 \cdot \Delta R - \delta_2 \cdot \Delta O \tag{5}$$

where α, β, γ, and δ represent coupling coefficients capturing interdependencies among mechanisms.

This representation illustrates that disturbances in one dimension can trigger cascading effects across others, forming feedback loops that amplify system-level failure. Although simplified, this formulation provides a structured way to capture nonlinear interactions and cross-stage feedback dynamics.

Although the four coupling mechanisms are conceptual in nature, they can be operationalized through measurable indicators in practical applications. For example, resource coupling may be assessed through redundancy levels and resource accessibility, information coupling through communication reliability and information latency, organizational coupling through coordination efficiency and decision-making clarity, and temporal coupling through response delays and recovery duration. These indicative metrics provide a basis for future empirical implementation and quantitative analysis.

3. Compound Hazard Scenarios and Stage-Coupled Failure Propagation

3.1. Analytical Strategy

In complex urban rail transit systems, emergency management is typically organized into multiple stages, including preparedness, response, and recovery. Although these stages are conceptually distinguished, they are strongly interdependent in practice. Decisions, resource configurations, and organizational arrangements established during preparedness may significantly influence operational effectiveness during response and recovery. Under compound hazard conditions, such interdependencies can create pathways through which disruptions propagate across stages, leading to stage-coupled failures.

To clarify these cross-stage interactions, this study conceptualizes four primary coupling mechanisms that link emergency management stages: resource coupling, information coupling, organizational coupling, and temporal coupling. Resource coupling refers to the availability and allocation of critical human, technical, and logistical resources required for emergency operations. Information coupling concerns the generation, transmission,

and interpretation of situational information among different actors and operational units. Organizational coupling reflects coordination structures, command relationships, and inter-agency collaboration mechanisms that shape collective responses. Temporal coupling captures timing dependencies between preparedness measures and subsequent response or recovery processes.

These mechanisms represent analytically distinct dimensions through which risks may propagate across emergency management stages. Although they may interact in practice, together they provide a coherent framework for examining stage-coupled failures under compound hazard conditions. The following sections analyze several representative scenarios to illustrate how compound hazards may activate these coupling mechanisms and generate cascading disruptions across the emergency management lifecycle.

3.2. Compound Hazard Context in Metro Stations

Metro stations are particularly susceptible to compound hazards due to spatial enclosure, high passenger density, and strong functional interdependencies among technical and organizational subsystems [45]. In such environments, multiple disruptive events often occur simultaneously or in close temporal proximity, placing concurrent demands on emergency management resources, information systems, and coordination structures. From a stage-coupling perspective, compound hazards are critical not only because they increase physical stress on infrastructure, but because they intensify interdependencies among emergency management stages. Under compound conditions, assumptions embedded in preparedness regarding resource availability, information continuity, and organizational coordination are more likely to be violated. As a result, failures that would otherwise remain localized can propagate across stages and escalate into system-level breakdowns.

3.3. Scenario Design

The compound hazard scenarios examined are not intended as empirical reconstructions of specific incidents. Instead, they are analytical archetypes that represent recurring patterns observed in metro station emergencies and documented across safety and transportation research. Scenario selection follows three criteria. First, scenarios must be operationally relevant to metro station contexts. Second, scenarios must activate multiple coupling mechanisms simultaneously. Third, scenarios must enable systematic tracing of failure propagation across preparedness, response, and recovery stages. Based on these criteria, three representative compound hazard configurations are examined: (1) fire combined with power outage, (2) earthquake combined with communication disruption, and (3) extreme weather combined with abnormal passenger congestion.

These compound hazard scenarios examined in this study are not arbitrary constructions but are derived from recurring patterns reported in prior research and documented metro emergency events. Specifically, combinations such as fire with power outage, earthquake with communication disruption, and extreme weather with abnormal passenger congestion have been frequently discussed in studies on urban rail transit safety and compound hazard interactions. These scenarios represent common multi-hazard interactions in metro systems, where multiple system failures or operational disruptions occur simultaneously or in close succession. Therefore, the selected scenarios are intended to represent analytically generalized patterns grounded in empirical observations reported in the literature, rather than isolated or hypothetical assumptions.

3.4. Representative Compound Hazard Scenarios

3.4.1. Fire–Power Outage

Fire–power outage scenarios have been widely reported in studies on metro fire safety and infrastructure interdependencies, where power system failures frequently co-occur

with fire emergencies. In fire and power outage scenarios, preparedness-stage vulnerabilities are primarily associated with resource configuration and redundancy design. Emergency plans commonly assume the availability of backup power systems to support lighting, ventilation, communication, and evacuation infrastructure. However, under compound conditions, backup systems may be limited in capacity, unevenly distributed, or insufficiently tested for simultaneous system stress. When fire coincides with power loss, resource coupling and information coupling are activated concurrently. Loss of lighting and reduced ventilation constrain evacuation and firefighting, while degraded communication undermines situational awareness and coordination. Response-stage actors are forced to adapt under severe constraints, relying on improvisation that is often insufficient when multiple subsystems are simultaneously degraded. These response-stage constraints propagate into recovery through temporal coupling. Prolonged evacuation and delayed hazard containment increase physical damage and resource depletion, extending restoration timelines and reducing recovery capacity. In this scenario, prolonged disruption reflects not hazard intensity alone, but the amplification of preparedness-stage resource deficiencies across emergency stages.

3.4.2. Earthquake–Communication Failure

Earthquake-induced disruptions to communication systems have been documented in multiple studies on infrastructure resilience, highlighting the vulnerability of information systems during seismic events. In earthquake scenarios accompanied by communication disruption, preparedness-stage assumptions regarding communication resilience become critical. While structural preparedness may be emphasized, insufficient redundancy and integration in communication systems create latent vulnerabilities that remain unnoticed under routine conditions. During response, information coupling and organizational coupling dominate failure propagation. Fragmented information flows lead to inconsistent situational interpretations across station staff, control centers, and external emergency services. At the same time, ambiguities in authority structures and coordination protocols delay collective decision-making and hinder effective evacuation and damage control. These failures are managerial in nature, arising from preparedness-stage design choices rather than physical damage alone. Recovery is subsequently constrained by incomplete damage assessments, delayed coordination, and organizational fatigue accumulated during response. The resulting disruption illustrates how information degradation during response propagates across stages, prolonging recovery and limiting adaptive learning.

3.4.3. Extreme Weather–Passenger Surge

Extreme weather events combined with passenger surges have been identified as a critical operational risk in urban rail systems, particularly during peak hours or service disruptions. When extreme weather coincides with abnormal passenger congestion, preparedness-stage capacity assumptions are rapidly exceeded. Emergency staffing levels, crowd management resources, and information dissemination mechanisms become insufficient under simultaneous operational stress. In this scenario, temporal coupling plays a dominant role in failure propagation. Delays in response compress recovery windows, while prolonged crowd control efforts exhaust personnel and equipment. Resource coupling and organizational coupling further reinforce temporal constraints, as limited staffing and fragmented coordination slow both response and recovery activities. The resulting disruption demonstrates how time pressure, once intensified by compound hazards, becomes a central mechanism through which stage-coupled failure unfolds. Failures escalate not because of extreme hazard severity, but because response delays and resource depletion systematically constrain recovery capacity.

While the three scenarios differ in hazard composition and operational context, they exhibit a convergent pattern of failure propagation across emergency management stages. Figure 3 synthesizes these patterns across the three scenarios, illustrating a common stage-coupled failure trajectory despite differences in hazard composition.

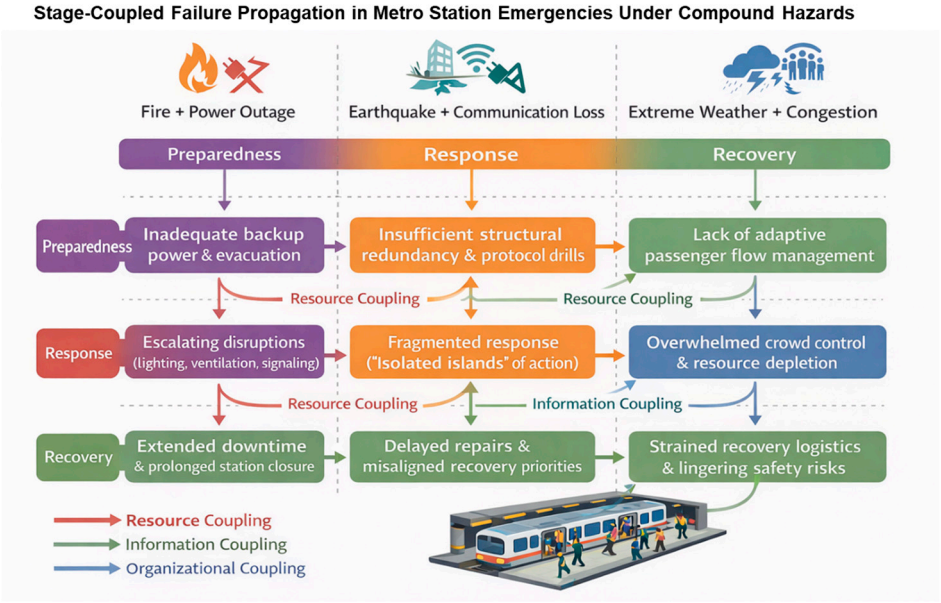


Figure 3. Cross-scenario synthesis of stage-coupled failure propagation under compound hazards.

3.5. Cross-Scenario Synthesis

The analysis results across the three scenarios reveal a consistent pattern of stage-coupled failure propagation. These results demonstrate how the four coupling mechanisms—resource, information, organizational, and temporal—systematically shape failure propagation across emergency management stages. Under compound hazards, response-stage adaptation is shaped—and often constrained—by activated coupling mechanisms involving resources, information, organizational coordination, and time. Failure propagation is nonlinear and interactional [46]. Resource shortages intensify information loss; information degradation amplifies organizational fragmentation; organizational breakdowns exacerbate temporal delays. These reinforcing interactions explain why emergency management systems that perform adequately under single-hazard or routine conditions may nevertheless experience cascading failures under compound hazard conditions. The severity of disruption observed in these scenarios cannot be explained solely by hazard characteristics. Instead, outcomes reflect the cumulative effects of cross-stage managerial and organizational interactions. This analysis demonstrates that stage-coupled failure is a systemic phenomenon, arising from the interaction of emergency management processes rather than isolated breakdowns. The ability of the framework to consistently explain failure propagation patterns across different scenarios provides indicative support for its analytical validity. These interactions can be interpreted as coupled dynamic processes, where disruptions in one dimension propagate and amplify across others through feedback loops.

3.6. Summary of Scenario Analysis

The analysis demonstrates how stage-coupled failure emerges and evolves under representative compound hazard configurations in metro stations. By tracing failure propagation across preparedness, response, and recovery, the analysis illustrates how coupling mechanisms amplify latent vulnerabilities and transform manageable disruptions

into prolonged system-level failures. The findings provide empirical grounding—at the level of analytical mechanisms—for the conceptual framework developed in Section 2. The next section discusses the broader implications of stage-coupled failure for safety science research and emergency management practice, with particular attention to systemic risk governance and resilience-oriented design. These findings provide analytical evidence supporting the explanatory capacity of the proposed framework.

4. Comparative Analysis and Theoretical Implications

4.1. Rethinking Emergency Management Under Compound Hazards

The analysis presented in Sections 2 and 3 demonstrates that emergency management failures in metro stations under compound hazard conditions rarely originate from a single decision, subsystem, or stage. Instead, failures emerge through cross-stage interactions in which managerial and organizational deficiencies are progressively amplified [47]. This result indicates that stage-based emergency management frameworks are insufficient under compound hazards. From a safety science perspective, this assumption becomes increasingly problematic as socio-technical systems grow more tightly coupled and exposed to compound hazards. When multiple disruptions occur simultaneously, the ability of emergency management systems to compartmentalize failures is significantly reduced. Safety performance becomes an emergent property of cross-stage coherence, rather than the sum of individual stage performances. The concept of stage-coupled failure provides an explanatory lens for understanding why emergency management systems that appear robust under routine or single-hazard conditions may nevertheless experience escalating breakdowns when confronted with compound hazards. It suggests that failure escalation is not an anomaly, but a predictable outcome of intensified coupling among emergency management stages. The consistency between the analyzed scenarios and patterns reported in prior studies suggests that the proposed framework captures generalizable features of compound hazard dynamics in metro systems.

4.2. Limits of Stage-Based Optimization

A central implication of this study is that stage-based optimization strategies are insufficient for managing safety under compound hazard conditions. Traditional approaches often focus on enhancing preparedness through planning and training, improving response through faster evacuation or decision-making, and accelerating recovery through efficient repair and restoration. While these efforts are necessary, the findings of this study indicate that they are not sufficient. Across the scenarios analyzed in Section 3, improvements in one stage were frequently constrained—or even undermined—by deficiencies in other stages. Preparedness investments that do not translate into accessible resources under degraded conditions provide limited safety benefits. Rapid response actions that exhaust personnel or deplete resources can prolong recovery and reduce long-term resilience. Recovery efforts are similarly shaped by the quality of information and coordination established during response. These dynamics highlight a critical limitation of stage-isolated evaluation metrics. Performance indicators such as evacuation time, response speed, or restoration duration capture outcomes within individual stages but fail to account for cross-stage trade-offs and amplification effects. From a stage-coupling perspective, safety outcomes must be evaluated in terms of how decisions and constraints propagate across stages rather than how each stage performs in isolation.

4.3. Theoretical Contributions

The proposed stage-coupled failure framework is compared with existing approaches, including stage-based emergency management models and technical cascading failure

models. The concept of stage-coupled failure contributes to safety science theory in several important ways. To clarify the theoretical positioning of stage-coupled failure within the safety science literature, Figure 4 compares the proposed concept with stage-based emergency management models and technical cascading failure models across key analytical dimensions. Compared with these approaches, the proposed framework captures cross-stage interactions and managerial mechanisms that are not addressed in conventional models. The semi-quantitative representation further provides a simplified formalization of these interactions, enabling clearer interpretation of feedback loops and nonlinear dynamics. The consistency of explanatory results across multiple scenarios suggests that the proposed framework provides a robust analytical lens for understanding cross-stage failure propagation.

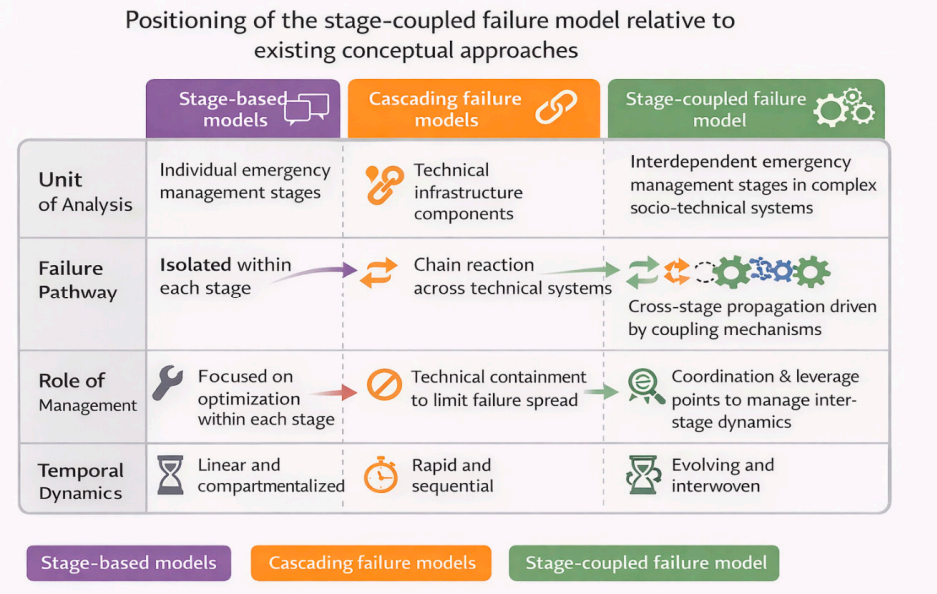


Figure 4. Conceptual positioning of stage-coupled failure within safety science research.

First, it shifts analytical attention from failure outcomes to failure processes. Rather than asking whether emergency management succeeded or failed at a particular stage, stage-coupled failure emphasizes how failures evolve and intensify through interactions among managerial processes over time. This process-oriented perspective complements existing accident and resilience theories by explaining not only what failed, but how and why failure escalation occurred. Second, stage-coupled failure extends research on cascading failures by explicitly incorporating managerial and organizational mechanisms. While cascading failure research has traditionally focused on physical interdependencies among technical components, this study demonstrates that similar propagation dynamics operate through management systems. In metro stations, where human decision-making and organizational coordination play a central role, these managerial pathways are often decisive in shaping safety outcomes. Third, the concept refines resilience theory by highlighting the relational nature of resilience capacities. Preparedness, response, and recovery capacities cannot be treated as independent attributes. Instead, their effectiveness depends on how they interact across stages under stress. Redundancy enhances resilience only if it remains accessible during response; rapid response supports resilience only if it facilitates sustainable recovery. Stage-coupled failure thus provides a framework for analyzing resilience as an emergent property of cross-stage interactions. Compared with stage-based models, the proposed framework captures cross-stage interactions rather than treating stages as independent. Compared with technical cascading failure models, it explicitly incorporates managerial

and organizational mechanisms as drivers of failure propagation. This highlights the added explanatory power of the proposed approach.

While this study does not rely on quantitative modeling, the proposed framework follows a mechanism-based analytical logic widely used in safety science for theory development in complex socio-technical systems. Such mechanism-based comparative analysis is widely used in theory-building research to evaluate explanatory power in the absence of direct empirical testing.

The proposed framework is also conceptually related to several established theories in safety science. For example, it complements Normal Accident Theory by extending the notion of tight coupling from technical systems to managerial processes. It aligns with High Reliability Organization Theory by highlighting the importance of coordination and adaptive capacity under high-risk conditions. It also resonates with Resilience Engineering by emphasizing the dynamic interactions among system functions across stages. These connections further support the theoretical relevance and integrative value of the proposed framework.

4.4. Managerial Implications

4.4.1. Resource Flexibility

Resource coupling emerged as a central mechanism of failure propagation across all scenarios. Preparedness-stage resource allocation should be evaluated not only in terms of sufficiency, but also in terms of deployability under degraded conditions. Backup systems, personnel reserves, and emergency equipment must remain accessible when power, communication, or mobility is compromised. Cross-stage drills that explicitly simulate compound hazards can help identify resource bottlenecks that remain invisible under single-hazard or routine training. Such exercises should focus on how resource constraints evolve across stages, rather than on isolated response actions.

4.4.2. Information Continuity

Information coupling played a dominant role in scenarios involving communication disruption and congestion. To mitigate information-induced failure propagation, emergency management systems must prioritize information continuity rather than information abundance. Redundant and decentralized communication channels can reduce vulnerability to single-point failures, but they must be complemented by shared sensemaking practices that enable actors to interpret and prioritize information under uncertainty. Information governance should extend beyond technical systems to include protocols for information verification, escalation, and cross-organizational sharing. Such measures can reduce the likelihood that information degradation during response constrains recovery planning and organizational learning.

4.4.3. Organizational Adaptability

Organizational coupling highlights the importance of flexibility in authority and coordination structures. Rigid hierarchies and narrowly defined roles may function adequately under routine conditions but become liabilities under compound hazards. Clear escalation protocols, pre-established inter-organizational relationships, and adaptive command arrangements can reduce coordination breakdowns and improve cross-stage continuity. From a stage-coupling perspective, organizational design should be evaluated based on its ability to remain functional under simultaneous stress across multiple stages, rather than its efficiency under normal operations.

4.4.4. Temporal Management

Temporal coupling underscores that time is not merely a constraint but a strategic resource in emergency management. Early-stage delays have disproportionate downstream effects, particularly on recovery. Managers should therefore adopt pacing strategies that balance rapid response with sustainability, avoiding actions that achieve short-term gains at the expense of long-term recovery capacity. Recognizing temporal coupling also implies that recovery considerations should be integrated into response decision-making, rather than treated as a separate post-emergency concern.

4.5. Governance Implications

At a broader level, the findings of this study suggest that resilience-oriented safety governance requires a shift from stage-based compliance toward process-oriented integration. Regulatory frameworks and performance metrics that focus exclusively on preparedness plans, response times, or recovery duration may fail to capture systemic risk arising from cross-stage interactions. Incorporating cross-stage performance indicators—such as the impact of response decisions on recovery duration—could improve oversight and incentivize integrative emergency management strategies. Post-event evaluations should similarly examine how failures are propagated across stages, rather than attributing outcomes to isolated errors or stages.

4.6. Discussion Summary

The analysis highlights the theoretical and managerial implications of stage-coupled failure for emergency management in metro stations. By demonstrating that failures under compound hazards emerge through cross-stage interactions rather than isolated breakdowns, the analysis highlights the limitations of stage-isolated optimization and underscores the need for integrative, process-oriented approaches to safety management. Together with the conceptual framework and scenario analysis presented in earlier sections, these findings advance safety science understanding of systemic risk in tightly coupled socio-technical systems and provide actionable insights for improving emergency management resilience under compound hazard conditions.

5. Conclusions

The results show that failure propagation in metro emergency management is fundamentally shaped by cross-stage interactions rather than isolated breakdowns. This study makes three main contributions. First, it introduces the concept of stage-coupled failure, shifting the focus from isolated technical failures to interdependent management processes. Second, it develops a framework based on resource, information, organizational, and temporal coupling mechanisms. Third, it provides a structured analytical approach using scenario-based analysis and semi-quantitative representation.

Rather than evaluating preparedness, response, and recovery as isolated phases, the analysis conceptualized emergency management as an interdependent socio-technical system in which managerial processes are tightly coupled across stages. The concept of stage-coupled failure shows that disruptions are often management-induced rather than hazard-driven. Failures emerge through systematic interactions among preparedness, response, and recovery, mediated by resource, information, organizational, and temporal coupling mechanisms. Under compound hazards, these couplings intensify, reducing the system's ability to contain disturbances and amplifying latent vulnerabilities across stages.

From a practical perspective, the findings underscore the importance of governing emergency management as an integrated system. Improving safety under compound hazards requires attention not only to individual stage performance, but also to the coupling

mechanisms that link stages. Enhancing resource flexibility, information continuity, organizational adaptability, and temporal awareness can reduce harmful coupling and support more resilient emergency management outcomes. Several limitations point to directions for future research. This study is primarily based on metro station environments characterized by significant human intervention in emergency management processes. As rail transit systems evolve toward higher levels of automation, particularly in fully automated operation systems (e.g., GoA4), the structure and dynamics of stage-coupled failure may change substantially. In highly automated and unattended stations, the role of human operators is reduced, and decision-making increasingly relies on algorithm-driven control systems. Under such conditions, failure propagation may shift from frontline organizational fatigue or coordination breakdowns to cross-stage error transmission mediated by algorithmic systems and digital infrastructure. These changes suggest that the coupling mechanisms identified in this study may manifest differently in automated contexts, requiring further investigation. Future research should therefore examine how stage-coupled failure evolves in smart and automated metro systems, particularly in relation to algorithmic decision-making, human–machine interaction, and system-level resilience.

As a conceptual study, the analysis does not empirically test the proposed mechanisms. The framework may also support practical applications such as safety audits, emergency planning evaluation, and scenario-based training in metro systems. Future research should focus on empirical validation, model refinement, and application of the framework to different metro systems and automated operational contexts. In addition, extending the framework to network-level analysis may provide further insight into how cross-stage failures propagate across multiple stations or infrastructure systems.

As system complexity and compound hazards increase, safety outcomes depend not only on doing individual emergency management stages better, but on understanding and governing the interactions that bind them together. By conceptualizing emergency management failure as a stage-coupled process, this study provides a foundation for more integrative and resilience-oriented approaches to safety governance in metro systems and other complex socio-technical environments.

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