



A VR-Based Training and Assessment Framework for Operational Resilience in Urban Metro Systems

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Resilience theory is central to the planning and operation of critical infrastructure, but its concepts are difficult to teach and assess in practice. This study presents an experimental VR-based instructional framework that makes resilience design concrete for metro emergency response. The study details the scenario design, logging scheme, and analysis pipeline. The framework develops a chain from observation indicators to outcome evaluation. Aligned with National Fire Protection Association 130 (NFPA 130) procedures, records a set of task times, operational accuracy, sequence adherence, and critical-error flags in a two-space scenario. These indicators are normalized to fixed criteria, mapped to resilience attributes, and aggregated into capability outcomes. The method is designed for facility and equipment management education and for workforce training. It provides objective grading, transparent feedback, and cohort performance.

Keywords: System Resilience, Virtual Reality Education, Emergency Training, Facility and Equipment Management, Urban Metro System

Introduction

Resilience offers a concept for understanding how systems prepare for, absorb, adapt to, and recover from disruptions (Lingua et al., 2023; Holling, 1973). With the development of resilience theory, it has expanded into broader fields (Zhou et al., 2024; Mehvar et al., 2021; Francis & Bekera, 2014) and has also become a guiding principle in policy in recent years. At the policy level, the United Nations Office for Disaster Risk Reduction (UNDRR) emphasizes not only loss reduction but also net resilience gains as a strategic objective for critical infrastructure investment (United Nations Office for Disaster Risk Reduction, 2022). It shows that the resilience of urban infrastructure systems is central to this agenda because service continuity and rapid recovery directly affect public safety and urban functionality.

Despite this conceptual progress, resilience remains difficult to teach and test. The concepts are abstract, and the learning effectiveness is not always observable in class or drills. The literature notes that while indices based on the widely embraced 4Rs framework (Robustness, Redundancy, Resourcefulness, and Rapidity) and performance metrics are well established, much of the work has emphasized loss and recovery time (Huang et al., 2025; De Iuliis et al., 2024; Roohi et al., 2024). The methods that connect learning activities to measurable gains in resourcefulness and rapidity are still limited. There is a need for a method that makes the theory concrete for learners and staff and that allows consistent assessment.

Immersive virtual reality (VR) training provides realistic, repeatable, and safe practice environments, which have been verified to be an effective strategy for improving personnel performance and safety cognition. Compared to traditional approaches, VR training consistently improves knowledge, procedural skill, and hazard recognition, along with practical advantages for repeat practice and cost over live drills (Wen & Gheisari, 2025; Marougkas et al., 2023). A VR-based approach can make resilience theory more understandable by linking learners' actions in simulation to system effects, and it enables consistent assessment of educational outcomes at the capability level.

This paper presents a VR-based training and assessment framework to convey resilience theory in a fire alarm emergency case of urban metro system (UMS) operations. Specifically, it proposes a tractable chain from observation to evaluation, maps VR indicators to capability-level outcomes, and implements a two-room scenario with a dual-mode workflow that aligns with NFPA 130 (National Fire Protection Association, 2023). The framework is designed to support teaching in facility and equipment management and workforce training, enabling both lab-based delivery and structured record-keeping. As a part of an ongoing project, this paper lays the groundwork for subsequent steps, including system development, classroom pilots, and comparative studies.

Literature Review

Resilience of Urban Infrastructure Systems and the 4Rs Framework

The concept of resilience describes an ecological system's ability to persist and absorb change in the face of disturbances (Holling, 1973). In the context of infrastructure, resilience evolved to contain a system's ability to resist, adapt to, and recover from disruptive events, such as natural disasters and technical issues. Bruneau et al. (2003) proposed a widely embraced framework that characterizes resilience through four key attributes: robustness, redundancy, resourcefulness, and rapidity.

Robustness is the ability of a system to withstand a given level of stress or demand without suffering degradation or loss of function (Keating et al., 2017). In UMS, this can refer to the fire resistance of structural components or the fail-safe design of critical equipment.

Redundancy is the extent to which elements, systems, or components are substitutable. It can maintain functionality in the event of the failure of other components, such as backup power supplies or multiple communication channels.

Resourcefulness is the capacity to identify problems, establish priorities, and mobilize resources when conditions threaten to disrupt the system (Amico & Currà, 2014). This includes mobilizing both material and human resources to meet established goals and manage the emergency effectively.

Rapidity is the capacity to meet priorities and achieve goals in a timely manner to contain losses and avoid future disruptions (Annarelli et al., 2020). This involves the speed at which critical functions, such as passenger evacuation and service restoration, can be accomplished.

Among these four properties, rapidity and resourcefulness are highly correlated with the performance of human and organizational systems (Wan et al., 2018). While robustness and redundancy are often engineered into the physical system during the design phase, resourcefulness and rapidity are heavily dependent on the capabilities of the personnel operating that system. The effective emergency response by frontline staff is a direct manifestation of resourcefulness and rapidity. A well-trained staff and team can skillfully arrange both tangible and intangible resources and execute complex procedures swiftly, significantly enhancing the overall system resilience (Ma et al., 2022).

However, a disconnect exists between this operational reality and current quantification methodologies. Extensive research primarily utilizes complex network theory and topology-based simulations to evaluate the impact of physical disturbances on system connectivity and efficiency (Mattsson & Jenelius, 2015; Zhang et al., 2015). These studies typically employ the performance response function to quantify resilience losses and recovery curves (Cimellaro et al., 2010; Ouyang et al., 2012). While such methodologies effectively measure structural robustness and redundancy, they often lack specific mechanisms to measure the micro-level operational resilience. Consequently, the rapid decision-making and problem-solving capabilities of frontline staff, which are identified above as critical drivers of recovery, remain largely unquantified in existing frameworks.

Application of VR in Safety Training for Architecture, Engineering, and Construction

VR technology has emerged as a powerful tool for safety training in the architecture, engineering, and construction sector. Its advantages over traditional methods, such as lectures or tabletop exercises, are well-documented, with recent studies highlighting superior outcomes in knowledge retention, engagement, and procedural adherence (Ishdorj et al., 2025; Chiu & Tsuei, 2025; Alshowair, A., et al., 2024). VR provides a highly immersive and engaging learning environment where trainees can experience realistic, high-risk scenarios without physical danger. Prior research using VR for training has shown consistent gains in knowledge, skills, and hazard recognition (Radianti et al., 2020). Because VR scenarios are repeatable, the system can automatically record objective performance data, which helps with feedback and skill retention. This setting supports procedural memory and decision-making under simulated stress.

At the same time, most disaster-preparedness applications still focus on narrow procedural tasks and individual outcomes, with limited attention to team coordination in complex socio-technical settings such as metro stations (Alshowair et al., 2024; Molka-Danielsen et al., 2018; Cohen et al., 2013). A further gap is the lack of a framework that links micro-level VR outcomes to macro-level resilience measures and to a measurable resilience gain at the system level (Hosseini et al., 2016; United Nations Office for Disaster Risk Reduction, 2022). This study addresses these gaps by proposing a compact framework that uses VR observations to produce capability-level learning outcomes aligned with resilience concepts, which can be adopted in teaching and workforce training.

VR-based training and assessment framework

Framework Overview

This study introduces a general framework that uses VR to convey operational resilience concepts in metro operations. The aim is to make abstract ideas observable and gradable so they can support learning for students and front-line staff. The framework follows a measurement chain shown in Figure 1. The blue-highlighted constructs denote the primary objects of analysis in this study: at the attribute level, the focus is on resourcefulness and rapidity; at the capability level, on absorptive, adaptive, and recovery capacities. First, the VR system records a set of objective performance indicators at action and phase level. Second, these indicators are mapped to resilience attributes that are sensitive to human and organizational actions, with emphasis on rapidity (how fast correct actions are taken) and resourcefulness (how well correct actions and sequences are selected and executed). Third, attribute values are aggregated into system capabilities that are meaningful for training and program evaluation. This chain preserves traceability from operational behavior to learning outcomes and constrains scenario design, logging, and reporting.

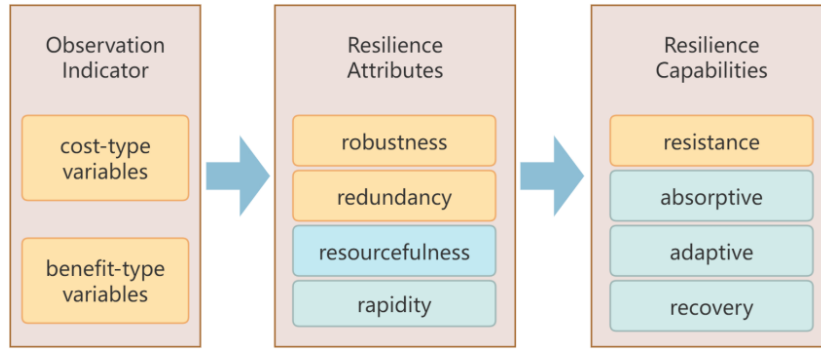


Figure 1. VR-based measurement chain for system resilience

Training Scenario Design Logic

The VR scenario operationalizes the procedural requirements of NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems for structured emergency response and staff preparedness. NFPA 130 Chapter 9 (National Fire Protection Association, 2023) emphasizes systematic and sequential response steps from incident verification to full passenger evacuation. Following this guidance, the training program is organized into four steps. The design implements, in order, incident verification, command communication, passenger management, and initial system control.

Figure 2 presents the full experimental workflow and the mapping of each phase to its key observation indicators. The workflow begins with the Alarm Trigger, which initiates the emergency response sequence.

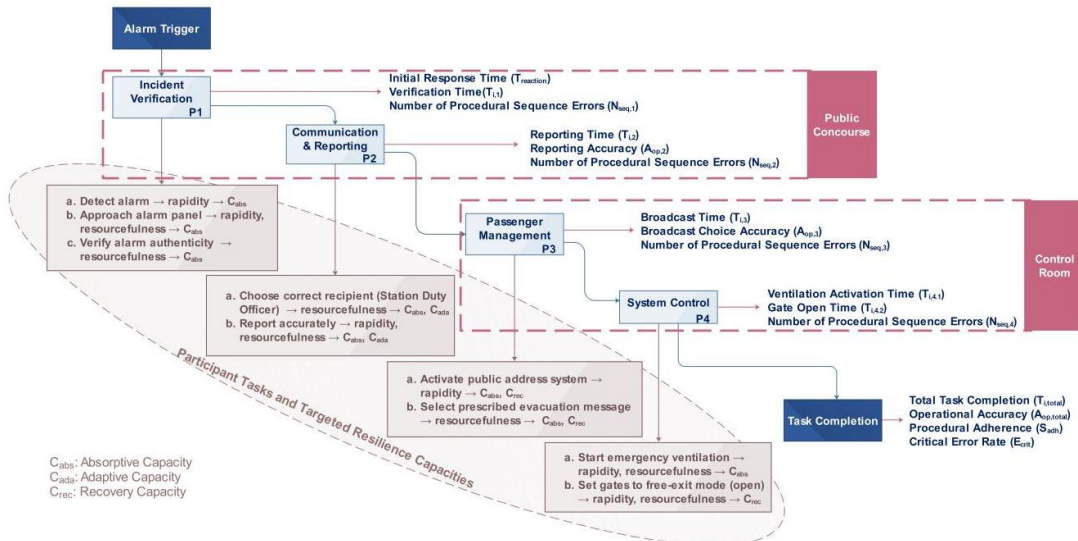


Figure 2. Structured phases and performance metrics in VR-based training program

Incident Verification (P1): The participant approaches the alarm location and then quickly moves to the alarm panel to verify the authenticity of the fire signal.

Communication & Reporting (P2): The participant selects the correct recipient (Station Duty Officer) and reports the incident accurately through their work communication devices.

Passenger Management (P3): From the control room, the participant activates the public address system and selects a prescribed evacuation message.

System Control (P4): The participant starts emergency ventilation and sets fare gates to free-exit mode at the operator console.

Data Processing and Assessment Methods

To keep the method practical and reproducible, the framework adopts a set of indicators that the VR platform can log automatically and consistently. Table 1 presents the indicators used in the framework linked to resilience attributes.

Table 1. Performance indicators mapped to resilience attributes

Indicator Type	Indicator	Explain	Resilience Attributes
Time-related indicators	Total Task Completion (T_{total})	Elapsed time from alarm trigger to completion of all required actions.	Rapidity
	Sub-task Duration (T_i)	Elapsed time for each phase or key action.	Rapidity
	Initial Response Time ($T_{reaction}$)	Elapsed time from alarm trigger to first correct action.	Rapidity
Accuracy and sequence indicators	Operational Accuracy (A_{op})	Proportion of required key actions executed correctly.	Resourcefulness
	Procedural Adherence (S_{adh})	Proportion of required steps executed in correct order.	Resourcefulness
	Critical Error Rate (E_{crit})	Proportion of errors that violate safety or control logic.	Resourcefulness

The VR engine records the indicators with the workflow: reaction time $T_{reaction}$, task times ($T_{i,1} \dots T_{i,4,2}$), operational accuracy for key selections $A_{op, k}$, procedural adherence derived from sequence errors (S_{adh} from the set $\{N_{seq, k}\}$), and critical-error flags E_{crit} . Movement time between spaces is logged but excluded from communication timing to avoid confounding.

For each indicator, this study set a minimum acceptable performance based on course requirements or standards and a proficiency target based on expert judgment or published benchmarks. Benefit-type indicators such as accuracy and adherence are scaled upward toward the target. Cost-type indicators such as times and error rates are inverted so that lower raw values become higher normalized scores. Simple percentile trimming is applied before scaling. All normalized indicators lie in $[0,1]$.

Normalized indicators are aggregated to rapidity and resourcefulness using fixed internal weights that sum to one within each attribute. The result is an attribute vector $R = \{R_{rap}, R_{res}\} \in [0,1]$. Attributes are mapped to capability scores using external weights that sum to 1 for each capability. For each capability $C_j \in [0,1]$, set a minimum competency threshold κ_j and a proficiency target τ_j with $0 \leq \kappa_j < \tau_j \leq 1$. A participant is classified as competent when $C_j \geq \kappa_j$ and as proficient when $C_j \geq \tau_j$. The normalized distance toward proficiency is $M_j = \max\{0, (C_j - \kappa_j) / (\tau_j - \kappa_j)\} \in [0,1]$. A scenario is

judged to contribute meaningfully to resilience knowledge when a predefined share of participants meet competency for the targeted capability and the cohort median $C_j \geq \kappa_j$ exceeds a course-level target.

System Implementation

VR Engine and Environment

The framework utilizes a simulation of the Gaoqiao Western Station in Nanjing, China, developed within the VR engine.. This module features a two-space layout designed to align with the emergency training workflow. It includes a public concourse for incident verification and on-site reporting, as well as a control room for passenger communication and system control.

The models are created in Revit and refined to include only the relevant elements for the tasks at hand: alarm sounder and panel, public address loudspeakers and console, ventilation switchboard, fare-gate bank, signage, and the operator console. Interactive objects are implemented as Unity prefabs, equipped with colliders, simple state machines, and event emitters to log key actions. Figure 3 presents two scenarios implemented within the VR engine.

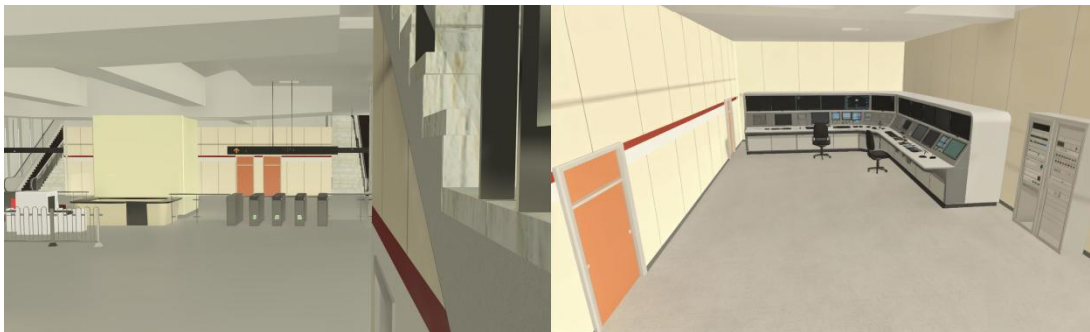


Figure 3. VR engine scenes for Gaoqiao Western Station: public concourse and control room

In the public concourse scenario, the participant first detects the alarm. Then, the participant approaches the alarm panel to verify the alarm status. After verification, the participant reports the alarm using the intercom. Next, the participant moves to the control room, activates the public address system, selects the appropriate message, initiates the emergency ventilation, and sets the gates to free-exit mode. Throughout both scenes, participants navigate in the first person and interact with panels using point-and-click actions. The engine records the time for each task, as well as operational accuracy, adherence to the required sequence, and flags any critical errors.

Experimental Condition

The experiment uses two experimental conditions to educate participants and measure their educational performance. Under training conditions, the participants receive brief on-screen guidance, and corrective messages are available to facilitate skill acquisition. In the assessment condition, the system removes guidance. Participants face minor controlled conditions designed to mitigate training effects and test transfer. For example, the interface introduces alternative device positions or reordered menu items. Instrumentation and the data schema remain identical across conditions, enabling a pre-post design with consistent measurements. Figure 4 presents the example of the training and assessment interface that participants saw.

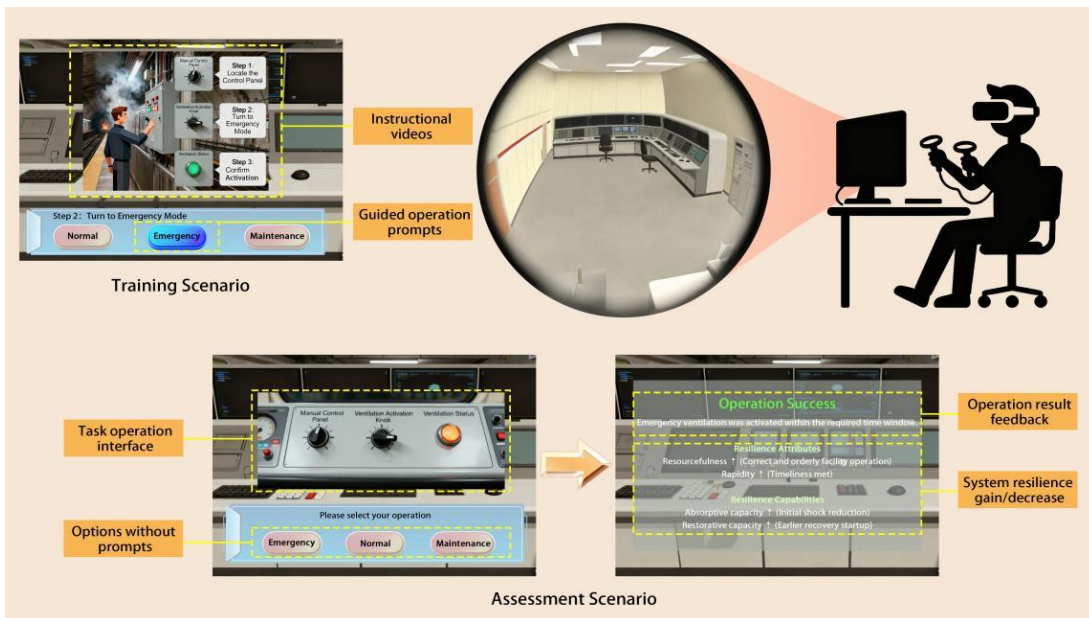


Figure 4. Interfaces for VR training and assessment scenario

Discussion

This study introduces a VR-enabled training and assessment framework that operationalizes resilience theory for metro emergency response and develops a method to assess learning through resilience attribution and resilience capability. The framework specifies a measurement chain that connects VR observations to resilience attributes and then to capability-level outcomes, uses time, accuracy, sequence adherence, and critical-error flags. It implements these measurements in a two-space VR scenario with separate training and assessment conditions. Additionally, it defines a reproducible assessment workflow based on fixed criteria and normalization.

This framework is applied in facility and equipment management teaching and can be delivered as a lab module that connects early actions to system reliability outcomes, providing objective grading and transparent feedback. Instructors can use common indicators across sections to compare cohorts and document learning progress at the course level. For metro operations, the framework supports periodic assessment, targeted remediation, and the creation of records documenting staff preparedness.

The next phase will focus on conducting pilot teaching with pre - post assessment to test whether the module improves capability scores and reduces critical errors relative to conventional instruction. Evaluating VR-based training against alternative methods such as classroom-based instruction, live drills, and onsite practice to identify the most effective or complementary combinations for different learner groups. Integration into facility and equipment management, teaching, and metro operation management will be explored through course pilots.

Conclusion

This study developed a VR-based framework for training and assessing resilience in a metro emergency response scenario. This framework translates observable actions into capability outcomes suitable for instruction and cohort reporting in training and assessment conditions scenarios. Additionally, the framework provides a set of indicators and thresholds, referring to adoption in facility and equipment management contexts and on-site staff training. The present work establishes the instructional logic and engine implementation. Future work will extend to team communication and multi-hazard cases, with follow-up on retention and transfer, supporting broader curricular and operational deployment.

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References

- Alshowair, A., Bail, J., AlSuwailem, F., Mostafa, A., & Abdel-Azeem, A. (2024). Use of virtual reality exercises in disaster preparedness training: A scoping review. *SAGE Open Medicine*, 12, 20503121241241936. <https://doi.org/10.1177/20503121241241936>
- Amico, A. D.', & Currà, E. (2014). The Role of Urban Built Heritage in Qualify and Quantify Resilience. *Specific Issues in Mediterranean City*. *Procedia Economics and Finance*, 18, 181–189. [https://doi.org/10.1016/s2212-5671\(14\)00929-0](https://doi.org/10.1016/s2212-5671(14)00929-0)
- Annarelli, A., Battistella, C., & Nonino, F. (2020). A framework to evaluate the effects of organizational resilience on service quality. *Sustainability*, 12(3), 958. <https://doi.org/10.3390/su12030958>
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & Winterfeldt, D. V. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake spectra*, 19(4), 733-752. <https://doi.org/10.1193/1.1623497>
- Chiu, J. I., & Tsuei, M. (2025). The effectiveness of using virtual reality to enhance safety education. *Educational Technology & Society*, 28(4), 19-41. <https://www.jstor.org/stable/48839354>
- Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures*, 32(11), 3639-3649. <https://doi.org/10.1016/j.engstruct.2010.08.008>
- Cohen, D., Sevdalis, N., Taylor, D., Kerr, K., Heys, M., Willett, K., Batrick, N., & Darzi, A. (2013). Emergency preparedness in the 21st century: Training and preparation modules in virtual environments. *Resuscitation*, 84(1), 78–84. <https://doi.org/10.1016/j.resuscitation.2012.05.014>
- De Iuliis, M., Cardoni, A., & Cimellaro, G. P. (2024). Resilience and safety of civil engineering systems and communities: A bibliometric analysis for mapping the state-of-the-art. *Safety Science*, 174, 106470. <https://doi.org/10.1016/j.ssci.2024.106470>

- Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, 121, 90–103. <https://doi.org/10.1016/j.ress.2013.07.004>
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1 – 23. <https://doi.org/10.1146/annurev.es.04.110173.000245>.
- Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering & System Safety*, 145, 47–61. <https://doi.org/10.1016/j.ress.2015.08.006>
- Huang, X., Yang, L., Wu, K., Tan, C., Qi, L., & Chen, Y. (2025). Study on the resilience recovery of civil airport infrastructure under weather extremes. *Natural Hazards*, 121(1), 1143–1163. <https://doi.org/10.1007/s11069-024-06814-8>
- Ishdorj, S., Kim, I., Ahn, C. R., & Kim, J. (2025). Effectiveness of VR Training and Observer-Based Learning for Complex and High-Risk Construction Task Performance. *Journal of Management in Engineering*, 41(6), 04025050. <https://doi.org/10.1061/JMENEA.MEENG-6834>
- Keating, A., Campbell, K., Szoenyi, M., McQuistan, C., Nash, D., & Burer, M. (2017). Development and testing of a community flood resilience measurement tool. *Natural Hazards and Earth System Sciences*, 17(1), 77–101. <https://doi.org/10.5194/nhess-17-77-2017>
- Lingua, C., Crespi, G., Becchio, C., & Corgnati, S. P. (2023). Designing IAQ-resilient post-pandemic buildings. *Sustainability*, 15(3), 2187. <https://doi.org/10.3390/su15032187>
- Ma, Z., Yang, X., Wu, J., Chen, A., Wei, Y., & Gao, Z. (2022). Measuring the resilience of an urban rail transit network: A multi-dimensional evaluation model. *Transport Policy*, 129, 38–50. <https://doi.org/10.1016/j.tranpol.2022.10.003>
- Maroukgas, A., Troussas, C., Krouska, A., & Sgouropoulou, C. (2023). Virtual reality in education: A review of learning theories, approaches and methodologies for the last decade. *Electronics*, 12(13), 2832. <https://doi.org/10.3390/electronics12132832>
- Mattsson, L. G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems-A discussion of recent research. *Transportation Research Part A: Policy and Practice*, 81, 16-34. <https://doi.org/10.1016/j.tra.2015.06.002>
- Mehvar, S., Wijnberg, K., Borsje, B., Kerle, N., Schraagen, J. M., Vinke-de Kruijf, J., Geurs, K., Hartmann, A., Hogeboom, R., & Hulscher, S. (2021). Towards resilient vital infrastructure systems—challenges, opportunities, and future research agenda. *Natural Hazards and Earth System Sciences*, 21(5), 1383–1407. <https://doi.org/10.5194/nhess-21-1383-2021>
- Molka-Danielsen, J., Prasolova-Førland, E., Fominykh, M., & Lamb, K. (2018). Use of a collaborative virtual reality simulation for multi-professional training in emergency management communications. 2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE), 408–415. <https://doi.org/10.1109/TALE.2018.8615147>

- National Fire Protection Association. (2023). NFPA 130: Standard for fixed guideway transit and passenger rail systems. National Fire Protection Association. <https://www.nfpa.org/codes-and-standards/detail?code=130>
- Ouyang, M., Dueñas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. *Structural Safety*, 36, 23-31. <https://doi.org/10.1016/j.strusafe.2011.12.004>
- Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, 147, 103778. <https://doi.org/10.1016/j.compedu.2019.103778>
- Roohi, M., Ghasemi, S., Sediek, O., Jeon, H., van de Lindt, J. W., Shields, M., Hamideh, S., & Cutler, H. (2024). Multi-disciplinary seismic resilience modeling for developing mitigation policies and recovery planning. *Resilient Cities and Structures*, 3(2), 66–84. <https://doi.org/10.1016/j.rcns.2024.07.003>
- United Nations Office for Disaster Risk Reduction. (2022). Principles for resilient infrastructure. <https://www.undrr.org/media/78694/download>
- Wan, C., Yang, Z., Zhang, D., Yan, X., & Fan, S. (2018). Resilience in transportation systems: A systematic review and future directions. *Transport Reviews*, 38(4), 479–498. <https://doi.org/10.1080/01441647.2017.1383532>
- Wen, J., & Gheisari, M. (2025). VR Women: Attracting Female Students to Construction through Immersive Storytelling. *Journal of Construction Engineering and Management*, 151(10), 04025142. <https://doi.org/10.1061/JCEMD4.COENG-16041>
- Zhang, X., Miller-Hooks, E., & Denny, K. (2015). Assessing the role of network topology in transportation network resilience. *Journal of Transport Geography*, 46, 35-45. <https://doi.org/10.1016/j.jtrangeo.2015.05.006>
- Zhou, S., Diao, H., Wang, M., Jia, W., Wang, Y., Liu, Z., Gan, W., Zhou, M., Wu, Z., & Zhao, Z. (2024). Knowledge mapping and emerging trends of urban resilient infrastructure research in urban studies: Precedent work, current progress and future perspectives. *Journal of Cleaner Production*, 452, 142087. <https://doi.org/10.1016/j.jclepro.2024.142087>