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Advancing Resilience Across Lifeline Infrastructure Systems: The Need for Consistent Guidance

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ABSTRACT

Consistent resilience guidance is needed to address the performance and recovery of lifeline infrastructure systems during and after hazard events. Lifeline infrastructure systems (e.g., water, wastewater, electric power, gas and liquid fuel, communication, and transportation systems) are interconnected and interdependent; each cannot operate normally or recover after an event without the services of the others. Social and economic activities also depend on lifelines and communities cannot be resilient if the infrastructure system services are not restored in a timely manner. Unfortunately, no system-level guidelines or standards exist to maintain service continuity and achieve rapid recovery following hazard events. Advancing resilience across lifeline infrastructure sectors requires improvements in (a) objectives for providing interdependent services needed by users during and after various hazard events, (b) design guidance for new and existing infrastructure to achieve those objectives, and (c) identifying and prioritizing organizational actions to support performance and recovery objectives. Formulating these into an overarching process helps each lifeline achieve consistent performance and service recovery. Lifeline-focused guidance then outlines asset and organizational action procedures, respectively, for designing the connecting components within each system and establishing strategies for the essential organizational groups. This guidance also provides direction for modifying existing or developing new system, component, and organizational group level guidelines and standards. NIST SP 1310 and 1311, entitled "Initial Framework to Design Lifeline Infrastructure for Post-Earthquake Functional Recovery," uses a similar approach for water, wastewater, and electric power systems, which is explored in this paper. This work also shows how the framework for post-earthquake recovery can be extended to other hazards and systems.

Keywords: Guidelines, Lifeline Infrastructure, Resilience, Performance, Recovery

INTRODUCTION

Lifeline infrastructure systems (e.g., water, wastewater, energy, communication, and transportation systems) provide services to meet social and economic needs of communities. Lifeline infrastructures are socio-technical systems that provide services through the integration of physical infrastructure and the human agency that operates it. To support community hazard resilience, service disruptions should be limited, and recovery activities should address societal needs. Resilience thinking acknowledges that service disruption from infrastructure systems cannot be completely prevented in a severe hazard event, but service recovery to customers and users when needed can be managed.

The performance of infrastructure under normal operating conditions as well as extreme loading is a key consideration in assessing and enhancing community resilience. Accordingly, lifeline infrastructure system resilience deals with the restoration of disrupted services and recovery of system reliability after hazard events to support impacted communities. However, current codes and standards generally do not explicitly consider the function of an infrastructure system or its components in establishing the desired performance in hazard events. Usually, safety is the primary, and often the only, criterion (RRMC, 2019). The lifeline infrastructure performance and service recovery objectives should be dictated by community resilience goals, yet most communities have never established any. A major challenge related to the development of community-resilience-based performance guidelines and standards is ensuring consistency in the performance assessment metrics and methods across different lifeline infrastructure system sectors (RRMC, 2019).

Lifeline infrastructure systems are interconnected and interdependent because each provides services to the others, and many are co-located. This means that the operation and provision of services from one depends on, or is critical to, the other systems. As a result, their designs and organizational actions must have consistency to meet a minimum performance level and the ability to recover services in an orderly manner to support the resilience of communities to hazards. NIST SP 1310 and 1311 presented the first framework of its kind to provide guidance on how to design lifeline infrastructure systems and align their performances and functional recoveries to meet societal needs following an earthquake.

This paper addresses the need for overarching guidance and presents processes to establish consistent procedures for designing, upgrading, and operating across all lifeline infrastructure sectors in response to hazard events. Consistency is necessary to align their performances and provide the orderly recovery of disrupted services to support community functions. The relationship between lifeline infrastructure services and essential community functions is reviewed. A linkage between community, building, and lifeline infrastructure system objectives is summarized. From this, processes are presented to create consistent procedures for lifeline infrastructure design and organizational actions. The processes first cover overarching design and organizational action procedures applicable to all lifeline infrastructure. The next part of the processes covers preparation of consistent design and organizational action procedures specific for each lifeline sector that is enabled by the overarching guidance. The third part of the processes addresses components and organizational groups making up each lifeline to respectively entail specific specialized designs and organizational policies and strategies consistently across the systems. The procedures can be documented in guidelines and standards. In this context, the term 'design' refers to developing new and upgrading existing infrastructure components and systems in the same way that policies and strategies may apply to existing organizational groups or the creation of new ones.

Recent frameworks (NIST 20,24a; Davis et al., 2023; ALA, 2005) prepared for seismic hazards are described to illustrate how the processes and procedures can be applied to improve lifeline infrastructure earthquake resilience. Methods for addressing other hazards are also considered.

DEVELOPING LIFELINE INFRASTRUCTURE RESILIENCE GUIDANCE

During and following damaging natural hazard events, performance of each lifeline infrastructure sector and interaction among multiple sectors is of critical importance to community resilience. Designing each of these interdependent systems and their components and establishing related organizational actions for a set of coherent objectives can help them operate as intended before, during, and after hazard events. The designs and organizational actions need to address how the infrastructure will perform (1) during events, in terms of potential for damage, service disruption, and operational continuity, and (2) following events, in terms of service recovery and restoring long-term functional and operational reliability.

Community-Level Resilience Goals

Ideally, community-level resilience goals for the various social and economic systems would first be established and applied across communities, from which lifeline infrastructure objectives would be developed and aligned with similar objectives for building clusters (RRMC, 2019). Although guidance on planning for community resilience exists (e.g., NIST, 2015; Rockefeller Foundation and ARUP, 2014), not all community resilience plans establish a set of performance and recovery goals, but the plans may identify that goals need to be documented (e.g., City of Los Angeles, 2018). Additionally, a systematic consensus-driven process for establishing links from community resilience goals to building and lifeline infrastructure objectives is not yet available (RRMC, 2019); because of its complexity and enormity, these proposed formal links are difficult to achieve and require significantly more research. Furthermore, most communities are not yet developing resilience goals, while interest and demands for improving lifeline infrastructure resilience are intensifying and spreading as the impacts from hazards increase around the world (United Nations, 2016). Even if all communities established their own resilience goals as proposed by NIST (2015), it would be difficult for lifeline infrastructure that serves multiple communities to meet a differing set of goals created by each community at different times. As a result, ***coordinated guidance for improving resilience for all infrastructure sectors must proceed now by incorporating flexible methods to meet the needs of vital community functions during and following hazard events. It is believed that a well-thought-out process can be implemented based on a premise that most vital or essential community functions are similar across communities (e.g., a hospital is critical to community recovery no matter where it is located)***. The lifeline infrastructure objectives can later be synchronized with future community-level consensus driven processes for developing community resilience goals.

The approach presented in this paper was originally created for an existing lifeline infrastructure system using performance-based design processes for earthquakes (Davis, 2017; Davis, 2019; LADWP, 2019) in the absence of community resilience goals.

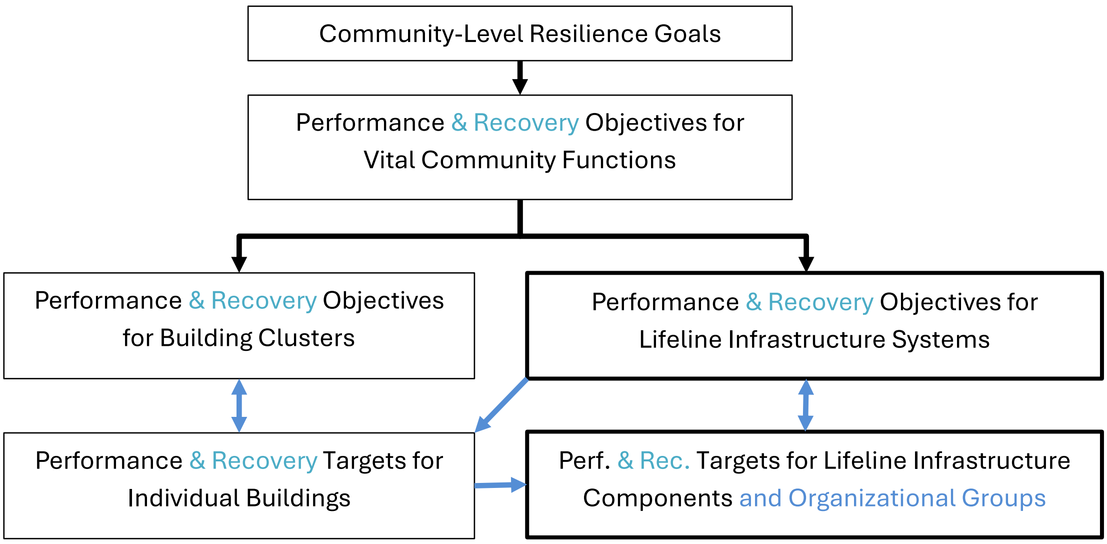

Figure 1. Process linking community-level resilience goals with buildings and lifeline infrastructure performance and recovery objectives and targets (modifications from RRMC, 2019 shown in blue).

Fig. 1 shows an aspirational approach for establishing resilience objectives for buildings and lifeline infrastructure from community-level resilience goals modified from RRMC's (2019) original vision. The goals, objectives, and targets in Fig. 1 are shown in an ascending order with highest importance at the top, and each level giving direction for the next. First, a policy-driven process is carried out to establish community-level resilience goals, which are used to derive performance and recovery objectives for a set of vital community functions and their supporting infrastructure (i.e., the building clusters and lifeline infrastructure) and link with performance and recovery targets for individual buildings and lifeline infrastructure components and associated organizational groups. Building clusters are defined as a set of buildings serving a common function, such as housing, healthcare, or retail, without necessarily being geographically collocated (NIST, 2015). Much effort remains to accomplish a policy-driven process to establish community resilience goals and derive objectives for vital community functions (RRMC, 2019). However, once accomplished, the building cluster and lifeline infrastructure objectives can easily be linked to support the vital community functions in meeting their objectives. For example, a hospital can establish a simple linear relationship with supporting infrastructure that it requires services within a specified duration after a disruption (e.g., potable water within a number of hours after an earthquake of specified magnitude).

System-Level, Component-Level, and Organizational Group-Level Performance

All lifeline infrastructures are socio-technical systems (IRRG, 2023; NIST, 2024a) made up of physical components (i.e., built assets) and human agency (i.e., organizational actions). For each system, the organizational group and physical component performances interlink as described by NIST (2024a). The performance and recovery expected for each component making up the system during and following hazard events dictate the organizational actions to be taken. For example, systems made up of highly fragile components to a specific hazard are expected to suffer severe damage and prolonged service disruption to an associated event. This requires a large effort for long durations by the organization during and following such an event. Whereas, for the same event, a system having components that are not fragile would not be expected to have as significant organizational activities during or following the event to maintain or recover services. As a result, ***there must be parallel organizational actions objectives consistent with the component objectives for lifeline infrastructure***. These are included in the lower right box of Fig. 1.

The process in Fig. 1 is modified from its original form (RRMC, 2019) to illustrate how performance and recovery targets for lifeline infrastructure components and groups are coupled with the ordered flow of importance defined by the arrows. The component and group target performances and recoveries must be informed by the system-level objectives and established with the aim of upholding these objectives. The complex nature of lifeline infrastructure does not allow a simple linear relationship between system-level objectives and each component or group because of emergent behavior that results from redundancies, interdependencies, human activities, and other important aspects summarized in NIST (2016a), NIST-FEMA (2021), NIST (2024a), and IRRG (2023). As a result, Fig. 1 shows a bidirectional link between the system and components/groups, indicating how the ***system objectives inform the component/group target performance and recovery and how the component/group target performances and recoveries support the system-level objectives***. Similarly, there is a bidirectional link in Fig. 1 between the building clusters and individual buildings. This means that there is a non-linear interaction between the system and component/group objectives, and likewise between the building cluster and building objectives. This affects the design process as explained below.

Lifeline infrastructure comprise various types of building structures, which are generally identified as individual components within the system. As a result, Fig. 1 shows a one-directional linkage from the lifeline infrastructure objectives to the individual building target performance and recovery and from the individual buildings to the lifeline infrastructure components target performance and recovery. These linkages reflect how the ***lifeline infrastructure objectives inform the building structures making up parts of the system and how the target performance and recovery of individual buildings, as system components, support the lifeline infrastructure system objectives***. Building structures serving a function within a lifeline infrastructure system may have different performance and recovery targets than a similar building that is not part of the system (e.g., office or maintenance building).

This paper focuses on the lifeline infrastructure system performance and recovery objectives and the component and organizational group target performance and recovery. These boxes are highlighted with bold lines in Fig. 1.

Performance Objectives and Recovery Time Objectives

Objectives serve as input for infrastructure design, organizational actions, and assessment processes. Performance is described in terms of (1) how the components, organizational groups, and systems fare during the event, i.e. the amount of damage and associated services that may be lost because of a hazard strike, and (2) the recovery over time. The first aspect is termed the performance objective and relates to how robust (Bruneau et al., 2003) the components, organizational groups, and system are to the hazard(s). After a hazard reduces the pre-event performance, there is a duration required to recover the services back to or near pre-event conditions. The second aspect relates to resilience rapidity (Bruneau et al., 2003) and is termed the recovery time objective. The objectives are defined as follows for lifeline infrastructure:

- **Performance Objective:** The planned damage or impaired state of assets and the organization for a specified hazard scenario event level.
- **Recovery Time Objective:** The planned duration to restore basic services for a specified hazard scenario event level.

NIST-FEMA (2021, pg 24) indicates how criteria should consider system-, component-, and group-level performance and recovery. Each component, set of components, group, organization, or subsystem must have criteria that are consistent with overall system performance and recovery objectives. System-, component-, and group-level performances and recoveries should be identified using a consistent set of metrics and evaluation methods for quantifying. Because all the systems are interdependent, and the dependencies are defined by services and not specific infrastructure (NIST, 2016b; 2024a), the system-level metrics should be established using services. Resilience can be greater improved and refined when the metrics are defined in terms of basic services (Davis, 2019; Davis et al., 2023; NIST, 2024a). The component and group level metrics can also be defined in terms of the amount of expected damage, ability to continue to operate, and repair/recovery time. The metrics for system-level performance and recovery, component-level designs, and organizational policies and strategies are to be associated with hazard intensity levels in relation to the consequences resulting from the hazards when they may strike.

To support community-level resilience goals as indicated in Fig. 1, there is a need to establish a link between the design, construction, and retrofit of individual buildings and lifeline infrastructure, and community resilience, as measured by time to recovery of function; but this link is currently missing (NIST-FEMA, 2021, pg. vi). However, Davis et al. (2023) and NIST (2024a) identify the means for ***lifeline infrastructure to establish service recovery times to different customers and users based on their importance to community recovery following hazard events***. The performance and recovery time objectives can differ for each lifeline infrastructure system based on the dependencies each has on the others within specific communities. For example, restoration of potable water may depend on electric power and transportation, while restoration of electric power may depend on natural gas distribution; thus, natural gas and transportation services need to be restored for electric power service restoration, then potable water service may be restored. However, regardless of the recovery time of different services, ***the processes and procedures for each lifeline infrastructure system should be undertaken in a similar manner using the criticality of different customers and users to the recovery of the communities. Further, processes and procedures must consider the post-event duration to recover full system functionality, which is necessary to restore system reliability. Managerial policies need to establish system-level performance and recovery objectives so procedures for infrastructure design and organizational actions can be oriented consistently to meet them***.

Processes for Creating Consistent Guidance

This subsection presents processes for creating consistent performance and recovery across all lifelines. The processes are presented in diagrams that expand the bold boxes from Fig. 1 to cover lifeline infrastructure systems, component and organizational group performance, and recovery objectives. The processes also include the design and organizational actions necessary to align the performance and recovery to support community recovery. Consistent performance and recovery across all lifeline sectors is necessary to address their interdependencies, intra-dependencies, and coordination among the variety of owners and operators. Consistent operation and service recovery are critical and necessary, as described above. In the absence of consistency, it is difficult, if not impossible, to meet basic societal needs, and disasters are prolonged.

Fig. 2 presents a process covering three successive design procedures identified by the arrows starting from the overarching through the system-level, down to the component-level. The three tiers apply to developing new or upgrading/retrofitting existing infrastructure. Each box in Fig. 2 represents a procedure. The higher tier directs the details at the next lower level. The top tier identifies overarching resilience procedures to apply for all lifeline infrastructure systems. The different lifeline infrastructure sectors were identified in the introduction. Fig. 2 identifies L different types of lifeline infrastructure sectors and N_i components making up each system. The number of lifeline infrastructure systems will vary by community and can be determined once all the types of systems and primary subsystems are fully defined in different areas. Using the tier 1 overarching procedures, each sector in tier 2 can create their own lifeline infrastructure specific procedures. In this manner, all lifeline infrastructure designs will be aligned in accordance with the overarching guidance and have consistency through the performance and recovery time objectives as described in Fig. 1. The third tier aligns procedures for design of each component with the lifeline infrastructure specific guidance for each sector and creates consistency among all assets. The procedures at each tier can be documented in guidelines and standards. Example procedural steps are presented in the following section.

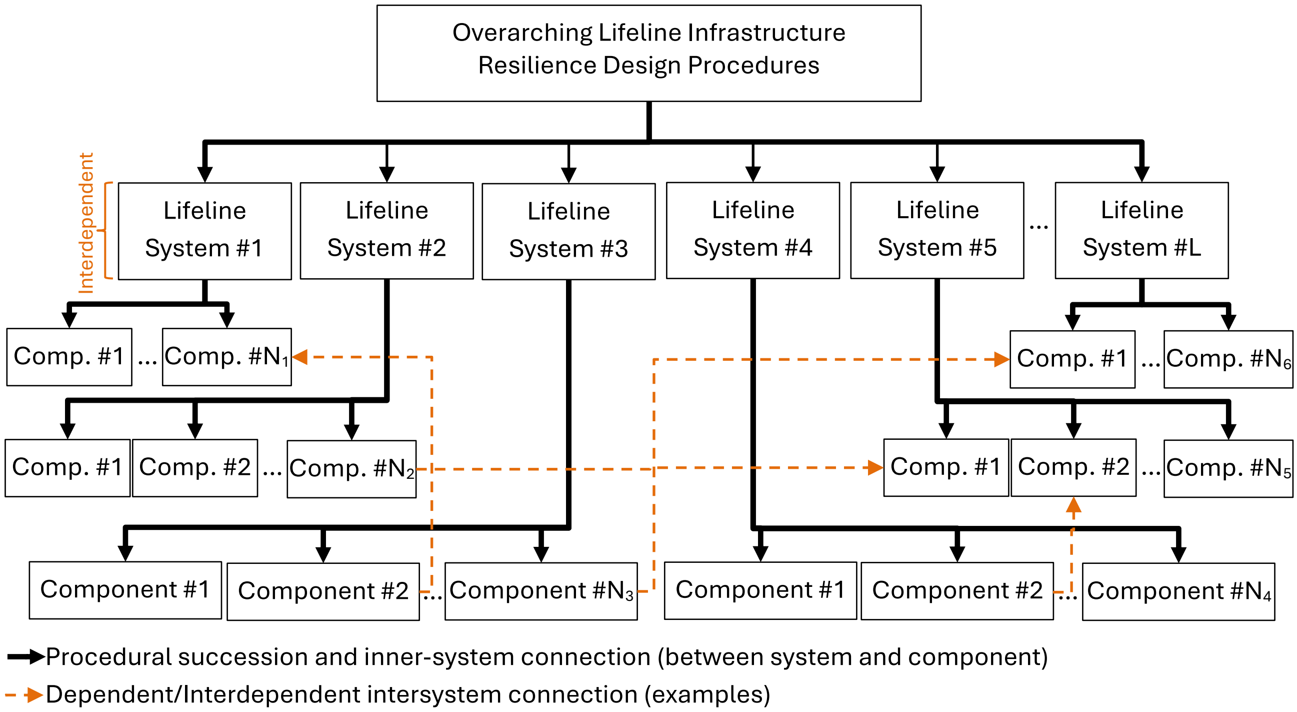

Figure 2. Process showing design procedures for lifeline infrastructure at three tiers (tier 1: overarching; tier 2: lifeline system specific; tier 3: component). Each tier has objectives associated with Fig. 1.

There are no existing system-level guidelines addressing the performance and service recovery of lifeline infrastructure systems (NIST, 2016a; 2022; RRMC, 2019). As a result, the overarching resilient design procedures and the lifeline system-specific procedures identified as the first two tiers in Fig. 2 are original concepts to be implemented into the lifeline infrastructure sectors. There are many different formal guidelines and standards for the wide variety of components making up the infrastructure systems, yet some components have never had any formal guidelines or standards developed for them for hazard exposures (e.g., seismic design of buried water and wastewater pipelines). To accommodate the lower tier in Fig. 2, existing procedures or guidelines for components can be modified to align with the system-level procedures and new procedures can be created for components where they are currently nonexistent.

As indicated in Fig. 2, all lifeline infrastructure is interdependent, meaning that the operation and provision of services of one system depends on, or is critical to, the other systems (Rinaldi et al., 2001; NIST, 2016a). Interdependencies are normally described in terms of how each system interacts with the others. However, the interdependencies are determined by how each system provides services to the others, and the services are provided through components from one system that interconnects to the others. In effect, these are service connections or access from each system to the others. In this context, the lines in Fig. 2 between the system-level (second row of boxes) and components (third and lower rows of boxes) represent inner system connections in addition to the flow of procedural succession. Fig. 2 provides example dependent interconnections with the dashed lines between components within different systems. Not all lifelines have interconnections within each community and most components in a single system do not interconnect with components in another system. However, in large urban areas most all lifeline infrastructure is interconnected (i.e., each provides services to all the other systems).

Fig. 3 shows a process and procedures for organizational actions that parallel those of Fig. 2 for infrastructure system and component design. The infrastructure system cannot recover without organizational actions, and to meet target service recovery objectives, the organizational actions must be consistent with the system-level and component-level performances. Each system's organizational structure may differ, but all are made up of groups that undertake activities to complete actions necessary for the system to operate and provide services to customers and users, including the other lifeline infrastructure.

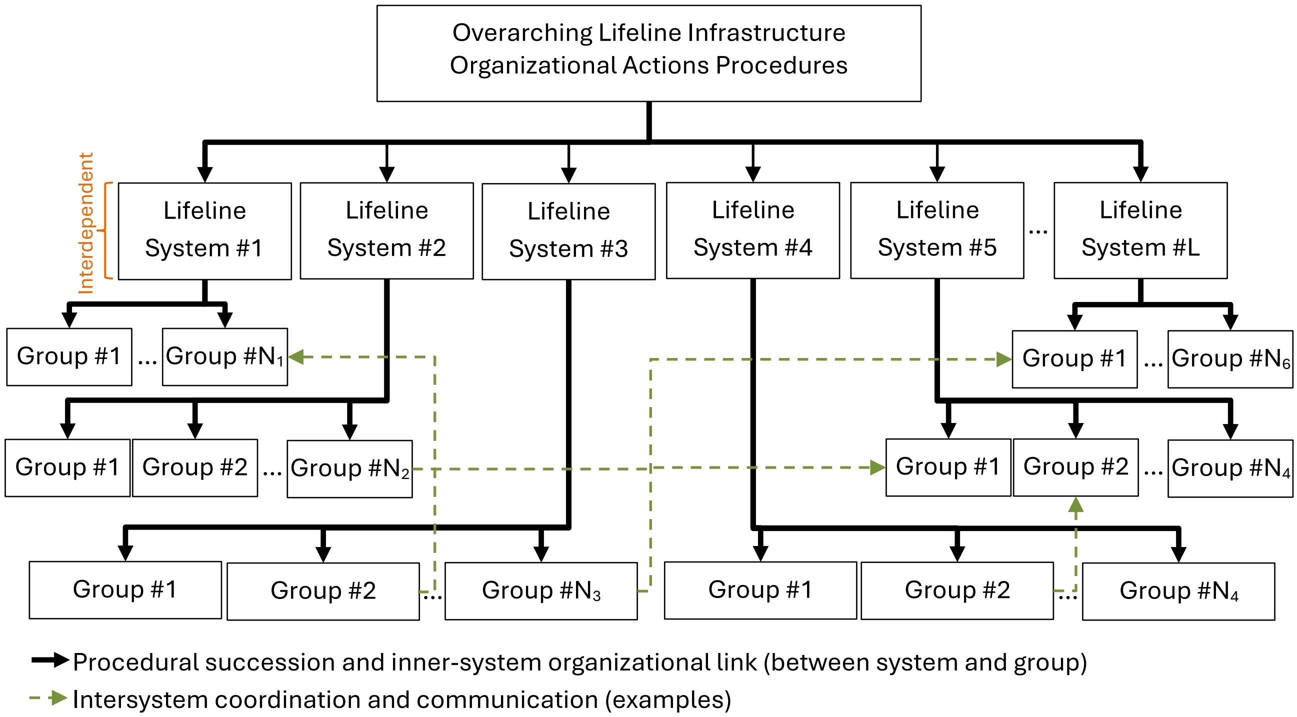

Figure 3. Process showing organizational action procedures for lifeline infrastructure at three tiers (tier 1: overarching; tier 2: lifeline system specific; tier 3: organizational group). Each tier has objectives associated with Fig. 1.

Fig. 3 is based on group-level achievements. The arrows identify the succession of procedures. Each group will have policies and procedures to perform during and following scenario events. The policies and procedures are associated with the overall system and different groups shown in Fig. 3, and different components shown in Fig. 2. Thus, components in Fig. 2 and groups in Fig. 3 are interlinked through lines perpendicular to the plane of the diagrams (i.e., out of the plane of the paper), but not all groups link with all components.

System-level and group-level guidance for establishing policies and strategies are commonly addressed in continuity planning (FEMA, 2018). The process shown in Fig. 3 is associated with the need to include group recovery time objectives to perform their activities, which currently are not included in normal continuity plans. As a result, using the process shown in Fig. 3 may require modification to continuity plans for defining essential functions, group recovery times, relationship with infrastructure fragility to hazards, and other aspects to improve the resilience of lifeline infrastructure organizations. Continuity planning (FEMA, 2018) and emergency management plans (FEMA, 2016, 2023) tend to serve as overarching guidance (i.e., first box in

Fig. 3) for lifelines organizations. The guidance should be updated based on the need to meet recovery objectives, and possibly for other aspects, to ensure consistency across all lifeline organizations. Each sector also tends to have lifeline specific continuity guidance (e.g., WRF, 2013). These and other associated documents will also need to be updated in relation to this proposed process structure. Further, each lifeline infrastructure organization may need to modify internal policies, strategies, and procedures to align with the resilience structure described for Figs. 2 and 3. Each of the three tiers in Fig. 3 includes performance and recovery time objectives associated with Fig. 1.

As shown in Fig. 3, the infrastructure systems are shown as being interdependent as described for Fig. 2, however the interdependencies are mainly observed through the services provided by the components. Organizational actions do support the service provision through the components but are indirectly associated with dependent services, so they are not shown in Fig. 3. The systems must coordinate to address the dependent services. The coordination is accomplished through proper communications between the system organizations which are made through different groups to meet the performance objectives identified in Fig. 1. In this context, the lines in Fig. 3 between the system-level (second row of boxes) and groups (third and lower rows of boxes) represent inner system organizational links in addition to the flow of procedural succession. Fig. 3 shows example coordination between different system organizational groups with dashed lines like those explained for dependent services in Fig. 2.

The application of Figs. 2 and 3 indicates that ***using the proposed guidance for each system is expected to achieve consistent performance with all the other systems. Similarly, the performance of each component within a system is expected to be consistent with the performance of all other components within the same system. Further, the performance of components within a single system is expected to have consistent performance with components within other lifeline infrastructure sectors.*** These performance levels are anticipated to reduce the potential impacts from dependent services (i.e., lower chance of dependent service disruptions between systems). For example, using Fig. 2, the Lifeline System #5 Component #1 has dependency on services from Lifeline System #2 Component #N_2. Through the guidance documents, the design level for System #2 Component #N_2 is consistent with providing the services to System #5 Component #1. This is accomplished by setting the performance and service recovery time objectives for System #2 Component #N_2 to meet the service needs of customer criticality defined by the importance of System #5 Component #1 and confirmed using a systems assessment as a validation on the system and component-level performances and recoveries for defined hazard scenario events. This may require coordination and communication among the different systems through their respective groups as presented in and described for Fig. 3.

The system assessment validation mentioned in the prior paragraph is recommended because the complex nature of lifeline infrastructure does not allow a simple linear relationship between component-level, organizational group-level, and system-level performance objectives as described for Fig. 1. As a result, even though the design of each component using consistent guidance improves component performance, it does not guarantee the system-level performance will meet the target objectives. Similarly, strategies for each group using consistent guidance improve group performance but do not guarantee system-level organizational performance will meet the target objectives. As previously explained, the component design and organizational actions are interlinked. ***To better understand the system-level performance, a system analysis of the built networks and organizational activities using recovery modeling is recommended*** and identified in the following section (see steps A9 and O8). Current practice addresses the design of built assets relatively independent of the organizational actions. ***The proposed tier 3 procedures in Figs. 2 and 3 attempt to change the dynamic by interlinking asset design and organizational actions to improve service recovery times***.

The RRMC (2019) identified that a major challenge related to the development of community-resilience-based performance guidelines and standards is ensuring some level of consistency in the performance assessment metrics and methods across different lifeline infrastructure systems. The significant differences in component types, spatial configurations, physical and functional interactions, and system interdependencies present major hurdles. The processes presented in Figs. 2 and 3 provide a methodology to overcome these challenges and hurdles.

APPLYING THE PROCESSES AND PROCEDURES FOR IMPROVING LIFELINE INFRASTRUCTURE RESILIENCE

Davis et al. (2024) summarize several frameworks recently developed for improving the functional recovery and resilience of lifeline infrastructure. Functional recovery can be summarized as restoring the use of interlinking components that need to be in minimum working order to recover lifeline infrastructure services after an earthquake. The frameworks describe how to prepare service recovery time objectives to meet community needs and develop consistent design procedures for system assets and organizational actions across all lifeline infrastructure. The service recovery objectives meet a portion of the lifeline infrastructure objectives identified in Fig. 1. The assets and organizational actions frameworks meet the overarching guidance identified in Figs. 2 and 3 and are applied to specific lifeline infrastructure showing how they meet the system specific guidance identified in the second row of boxes in Fig. 2. These frameworks were prepared for earthquakes and are expected to be applicable to other hazards with proper modification, as further discussed in the following section. They are summarized in the paragraphs below, followed by how specific component guidance is being prepared using the processes indicated in Figs. 1 and 2. The combination of documents presented in this section are the first to apply the procedures described in Figs. 1 to 3 for guidance to lifeline infrastructure. Due to space constraints, greater detail on each framework cannot be described. For interested readers, the cited references provide further information.

Davis et al. (2023) presents a procedure to prepare basic service recovery objectives for all lifeline infrastructure and has been applied to an example potable water system. This meets the objectives identified in Fig. 1 and the general procedure applies to the overarching guidance shown in the first box while the application to specific lifeline infrastructure applies to the second row of boxes in Figs. 2 and 3. The procedure is accomplished using the following seven steps. The objectives are used as input into the assets and organizational actions frameworks described below (NIST, 2024a, 2024b).

- Step 1: Define Lifeline Infrastructure System and Basic Service Categories
- Step 2: Identify Kinds of Uses for User Types
- Step 3: Identify Adaptations
- Step 4: Identify Sets of Conditions and Target Societal Impact Levels
- Step 5: Determine User Consequences from Service Interruption
- Step 6: Determine Target Recovery Times for Basic Services
- Step 7: Summarize Recovery Time with the Societal Impact Levels

NIST (2024a) covers the overarching guidance shown in the first box in Figs. 2 and 3 to design all lifeline infrastructure for functional recovery. The procedure is accomplished using eleven steps for the design of assets. In this context, assets are considered the same as components described throughout this paper.

- Step A1: Define System Layout and Operational Characteristics
- Step A2: Define Criticality Category and Earthquake Design Basis for System Components
- Step A3: Check Multiple Use, Continuity, and Redundancy
- Step A4: Establish Component Objectives - Maximum Level of Damage and Repair Time
- Step A5: Identify Dependent Services
- Step A6: Develop Preliminary Design
- Step A7: Assess the Component Performance and Repair Time, Compare with Target Objectives
- Step A8: Identify Recovery Time Factors
- Step A9: Assess System Performance and Recovery Time
- Step A10: Compare System Assessment Results with Target Objectives
- Step A11: Report System Assessment Results

The organizational actions framework in NIST (2024a) is accomplished using ten steps.

- Step O1: Identify Groups within the Organization and their Functions
- Step O2: Identify Organizational Essential Functions, Resources, and Groups
- Step O3: Assess Internal and External Coordination
- Step O4: Establish Responsibilities, Resources, Capabilities, and Recovery Time Objectives
- Step O5: Develop Group-Level Policies and Strategies
- Step O6: Assess Group Performance and Recovery Capability and Compare with Group's Target Objectives

- Step O7: Identify Recovery Time Factors
- Step O8: Assess System Performance and Recovery Time
- Step O9: Compare System Assessment Results with Target Objectives
- Step O10: Report System Assessment Results

NIST (2024b) applies the overarching guidance from NIST (2024a) to show how it can be applied to potable water, wastewater, and electric power systems for earthquakes. NIST (2024a) is also prepared to be applicable to all other lifeline infrastructure. As a result, NIST (2024b) shows how the lifeline specific guidance identified in the second row of boxes in Fig. 2 can be fulfilled using the same eleven steps A1 to A11 outlined above. Similarly, steps O1 to O10 can be applied to specific lifeline systems to address the second row of boxes in Fig. 3.

The only known document that interlinks the performance of assets with organizational actions for lifeline infrastructure is NIST (2024a). At present, the documents that provide guidance for lifeline infrastructure organizations (e.g., FEMA, 2016, 2018, 2023) are prepared relatively independent of asset performance. Implementing the processes proposed in Figs. 2 and 3 will change this dynamic and improve lifeline infrastructure resilience.

The American Lifelines Alliance (ALA, 2005) report provides target performance objectives and design criteria for the seismic design of buried water pipelines. In fact, the original development of the performance criteria in ALA (2005) used performance-based concepts for infrastructure networks and serves as the catalyst and was built upon and coupled with basic service concepts (Davis, 2014) to create component-level performance objectives that allow the system to meet post-event basic service recovery (Davis, 2014; 2019) when needed by customers to provide vital community functions. The concepts are formulated within the LADWP (2019), Davis (2017; 2019), and NIST (2024a) methodologies. Thus, ALA (2005) provides an example of how component level criteria can be used to meet component specific guidance consistent with system-level guidance. ALA (2005) is not a formal document because it was not vetted and approved by industry nor created by a standards developing organization. However, the American Society of Civil Engineers (ASCE) is currently in the process of developing a manual of practice for the seismic design of buried water and wastewater systems (e.g., Wham et al., 2019) that draws upon ALA (2005) and is consistent with NIST (2024a and 2024b) for water and wastewater systems with the aim of developing a formal industry reviewed and approved document and eventually creating a formal standard. Thus, when completed, the ASCE manual of practice and follow-up standards will be the first to complete the component-level documents within the process presented in Fig. 2 for infrastructure systems and components for earthquakes.

EXTENDING TO PROVIDE GUIDANCE FOR MULTIPLE HAZARDS

The documents summarized in the prior section were prepared specifically for earthquakes. However, they each identify how they may be extended to other hazards with additional research and appropriate modifications. The exact modifications needed are not yet fully identified, however, some of the aspects are anticipated to include:

- How to consistently characterize multiple different hazards for performance objectives (RRMC, 2019).
- Incorporating hazard forecasting opportunity. Unlike earthquakes, some hazards can be reliably forecast (e.g., severe storms, floods) and allow for pre-event organizational actions to take place to improve lifeline infrastructure resilience. Pre-event performance objectives may also be established for some hazards. For example, electric power systems currently have shutdowns when threatened by high winds to help prevent igniting wildfires. These shutdowns impact other lifeline infrastructure by disrupting the dependent services. Pre-event forecasting and associated actions are not currently incorporated into NIST (2024a).
- Incorporating hazard duration. Unlike earthquakes, some hazards can last for a sufficient duration within which some organizational actions can take place during the event (i.e., co-event). This also allows for co-event performance and recovery objectives for some lifeline infrastructure. For example, currently there are no wildfire hazard co-event hydraulic flow objectives for water distributions systems. The resilience to wildfires can be improved by establishing water supply and distribution system co-event fire flow objectives. Similar principles can be applied to other hazards, such as floods, hurricanes, and droughts. Co-event organizational activities and associated objectives are not currently included in NIST (2024a) or Davis et al. (2023).

CONCLUSIONS

The prevailing approach of setting performance targets for each component of the built environment, mainly based on life safety, property protection, and economic constraints, results in inconsistency across components and lifeline infrastructure systems and likely does not allow the community to confidently rely on the ability of their built environment to support social and economic functions after hazard events occur (RRMC, 2019). A new resilience-based approach is proposed to improve the lifeline infrastructure performance during events and service recovery following events. This approach establishes overarching procedures for the design and operation of all lifeline infrastructure, including the assets and organizational actions necessary for operation. Following the direction of the overarching procedures, lifeline system specific procedures can be made consistent across all sectors. Each sector then dictates procedures for design of all components making up the systems. Similarly, guidance for each lifeline organization can be structured to properly coordinate and communicate across systems. The process helps to remove independent siloed planning, decision making, and emergency operations among lifeline infrastructure.

The proposed processes and procedures have some initial efforts underway to be put into practice. NIST (2024a; 2024b) has used these concepts for creating initial steps for the design and organizational actions needed for functional recovery of lifeline infrastructure to earthquakes. ASCE is currently working on a seismic design manual of practice for buried water and wastewater pipelines, i.e., critical components of many infrastructure systems. The manual of practice is essentially following the process for consistent design procedures for components to ensure resilient systems that support the societal needs of communities. The proposed processes and procedures used for earthquake can be expanded for application to other hazards.

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