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COMMUNITY RESILIENCE OF LIFELINE SYSTEMS: SOCIETAL NEEDS AND PERFORMANCE ASSESSMENT

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Abstract

The concept of community resilience is a complex, multi-dimensional problem that relies on social science, engineering, earth sciences, economics, and other disciplines to improve the way communities prepare for, resist, respond to, and recover from disruptive events. Community resilience can break the cycle of destruction and recovery and reduce the impacts of earthquakes and other hazards. This requires community planning for recovery of function and setting of recovery goals prior to the occurrence of hazard events to minimize social and economic disruptions.

Investigations of lifeline system performance, interdependencies, and corresponding impacts on communities following earthquakes and other disasters around the world have highlighted the need for a new approach to improve the earthquake resilience of lifelines. In 2013, the National Institute of Standards and Technology (NIST) funded a project, led by the Applied Technology Council (ATC), that resulted in the NIST GCR 14-917-33 Report, *Earthquake Resilient Lifelines: NEHRP Research, Development, and Implementation Roadmap*. This report identified the need for assessing societal expectations of acceptable lifeline performance levels and recovery times at the community level as a high-priority research and development topic.

NIST funded a follow-on project in 2014 led by ATC to assess current societal expectations of acceptable lifeline performance levels and recovery timeframes, distinguishing those that are hazard independent and those that are specific to earthquakes (including tsunami), as well as other natural hazard events (ATC-126 Project). The team developed the NIST GCR 16-917-39 Report, *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*, which focuses on societal needs and interdependencies of six key lifelines: electric power, gas and liquid fuel, water, wastewater, telecommunications, and transportation networks.

The NIST GCR 16-917-39 Report identifies important gaps between expected lifeline system performance and the performance required to support adequately societal needs during and after a hazard event. Gaps were identified through an evaluation of performance and societal impacts during past events, as well as the assessment of key guidelines, standards and performance criteria that govern and shape the design, construction, operation and management of lifeline systems. The report identifies and discusses the social institutions and societal needs that should drive lifeline system performance levels and timeframes for recovery of function. Critical interdependencies, recommendations and needs particular to policy, modeling, research, and future trends for social needs and lifeline systems are included in the report. This report supports larger efforts, such as the Community Resilience Program and National Earthquake Hazards Reduction Program (NEHRP) at NIST, intended to help communities and lifeline owners and operators achieve a more integrated and consistent approach to resilience. The findings from this report, summarized in this paper, are intended to inform resilience efforts in the United States and other countries.

Keywords: Resilience; Lifelines; Social needs

1. Introduction

Resilience involves the ability of people and communities to adapt to changing conditions and withstand and rapidly recover from disruptions [1]. At the community level, this concept is complex and multi-dimensional, relying on contributions from social science, engineering, earth sciences, economics, and other disciplines to improve the ways communities prepare for, resist, respond to, and recover from disruptions resulting from either natural hazards or human causes. Resilience is intended to reduce the impact of hazards by restoring a community to normal function in a specified timeframe to minimize disruption, and in turn, reducing the duration and cost of recovery. This requires planning for recovery of physical, social, and economic functions and services prior to hazard events.

Disasters can substantially reduce a community's resilience by interfering with the operation of infrastructure, such as electric power, natural gas and liquid fuel, telecommunication, transportation, and water and wastewater systems (otherwise known within the earthquake engineering profession as "lifelines"). Lifelines are often distributed over large geographic regions and have numerous interdependent levels of operation, making them especially exposed to the impacts of earthquakes, hurricanes, and other hazards that affect broad areas. As a result, lifelines can experience distress and malfunction at many locations which, in turn, can impede response and recovery. Lifeline system failures and disruptions can displace people, disrupt social and economic institutions, and in the worst cases lead to death and long-term negative societal consequences.

In September 2014, the Applied Technology Council (ATC) commenced a task order project under National Institute of Standards and Technology (NIST) Contract SB1341-13-CQ-0009 to assess current societal expectations of acceptable lifeline performance levels and restoration timeframes that are informed by the phases of response and recovery, distinguishing those that are hazard independent and those that are specific for seismic (including tsunami), wind (including hurricane and tornado), flood, snow/ice, and wildfire hazard events.

The study was conducted as part of the NIST Community Resilience Program, a multi-year, multi-faceted program that is part of a broader disaster resilience effort that includes the oversight of the National Earthquake Hazards Reduction Program (NEHRP), which was established by the U.S. Congress with its passage of the Earthquake Hazards Reduction Act of 1977 [2]. NIST has served as the lead NEHRP agency since 2006, and has conducted numerous projects to meet NEHRP goals, including the effort described in this paper as well as the development by ATC of the NIST GCR 14-917-33 Report, *Earthquake Resilient Lifelines: NEHRP Research, Development, and Implementation Roadmap* [3], which identifies a wide range of needed studies and guides investments made by NIST and other NEHRP agencies in generating national performance and restoration goals and accompanying guidelines, manuals, and standards for lifeline systems and components.

Element I of the *Earthquake Resilient Lifelines Roadmap* identifies the priority research, development and implementation topics necessary for establishing national lifeline system performance and restoration goals. Topic 2 of Element I of the *Roadmap* specifically calls for a national assessment of societal expectations of acceptable lifeline performance levels and restoration times as a high-priority and a necessary part of the development of resilient design and construction goals for interdependent lifeline components, systems, and the communities those systems serve. While this roadmap specifically addresses resilience issues in the context of earthquakes, those priority research and development topics, including Topic 2, are valid for other hazards as well.

This paper includes consideration of the social institutions and societal needs that should drive lifeline system performance levels and recovery timeframes. It also provided an assessment of current system guidelines/standards and performance criteria. The assessment identifies deficits that could be potentially addressed through better awareness and definition of community requirements and goals as part of the overall Community Resilience Planning process [4].

The following sections discuss the project purpose, project development approach, principal findings, future considerations, and recommendations resulting from the study.

2. Project Purpose

The primary purpose of this study was to *assess current societal expectations of acceptable lifeline performance levels and recovery timeframes that are informed by the phases of response and recovery, distinguishing those that are hazard independent and those that are specific for seismic (including tsunami), wind (including hurricane and tornado), flood, snow/ice, and wildfire hazard events.* An additional goal of the study was to identify gaps between the desired and anticipated performance of lifeline systems to enable communities and lifeline system operators to set priorities and define strategies to reduce risks and improve lifeline resilience. In addition, this study was intended to provide a technical foundation for first-generation systems-based models that can be used to analyze community resilience and account for interdependencies among lifeline systems and the social and economic functions that they support.

The assessment described in this study is also intended to support the *Community Resilience Planning Guide for Buildings and Infrastructure Systems* [4]. The *Guide* defines a six-step voluntary process for engaging stakeholders and representatives to define key social and economic needs and community functions; develop an inventory of the community's building stock and infrastructure systems; establish performance goals for buildings and infrastructure to serve key social and economic needs over a range of different hazard types; identify and evaluate gaps between the desired and anticipated performance of buildings and infrastructure; and set priorities and define strategies to reduce risks and improve the resilience of buildings and infrastructure systems in their community. The *Guide* recommends that communities identify and plan for the prevailing hazard types (e.g., wind, earthquake, inundation, fire, snow or rain, and technological or human-caused) that may have a significant effect on their built environment. It also recommends consideration of a range of hazard levels defined as: *routine* (occurs frequently and is below the design level); *design* (often based on codes and standards); and *extreme* (above the design level and sometimes referred to as the maximum considered event).

3. Project Approach

Over the last 43 years the Applied Technology Council has employed a staffing model that consists of: (1) ATC staff specialists in earthquake and natural hazard mitigation, who have lead responsibility for defining the project work effort, identifying and engaging project consultants, carrying out needed quality control efforts, ensuring that the project products incorporate the intended scope, and managing all financial matters; (2) highly qualified technical consultants from private design practice and the research community, who are engaged to conduct detailed technical research and development work required of the project; and (3) leading specialists from structural engineering practice, the academic/research community, and the regulatory community who are engaged to serve on an "blue-ribbon" review panel to ensure that the project work products are technically accurate, complete, and reflect a broad spectrum of professional opinion.

Project staffing included an ATC Project Manager and Associate Project Manager, a Project Technical Committee consisting of a Project Director (an urban planning consultant), Project Co-Director (an academic pipeline system specialist), and six academic and private-sector consultants (a social scientist, an electric power system specialist, a telecommunication system specialist, a transportation system specialist, a water/wastewater system specialist, and a researcher specializing in lifeline system interdependencies), a blue ribbon Project Review Panel consisting of six academic and private-sector consultants (a researcher specializing in risk and reliability, an electric power system specialist, a natural gas and liquid fuel system specialist, a telecommunication system specialist, a transportation system specialist, and a design professional specializing in structural, earthquake and tsunami engineering).

The Project Technical Committee reviewed and summarized key lifelines guidelines, standards, and current performance criteria, and identified critical social considerations and system interdependencies. Those and subsequent efforts helped form a set of overarching considerations and project findings, which were then refined through several rounds of review by the Project Review Panel and NIST sponsors.

The culminating effort was the development of the NIST GCR 16-917-39 Report, *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery* [5], which contains:

- Detailed analyses of a broad range of societal considerations;
- Lifeline assessments and reviews of standards, guidelines, and performance criteria for electric power, natural gas and liquid fuel, telecommunication, transportation, water and wastewater systems;
- A review and analysis of available information on lifeline interdependency issues; and
- Findings, conclusions and recommendations that identify needed developments in lifeline codes, standards, and guidelines; needed research; modeling opportunities; and needs related to lifeline system operations and operational design.

4. Principal Findings

The principal findings of the study address the current state of lifeline codes, standards, guidelines, and performance requirements in the United States; overarching societal considerations; critical interdependencies; disaster lessons (short-, intermediate-, and long-term recovery); key gaps and deficits; and future trends and considerations.

4.1 Current State of Lifeline Codes, Standards, Guidelines, and Performance Requirements

A survey was conducted of the codes, standards, guidelines and manuals that govern the design, construction and performance of key electric power, natural gas and liquid fuel, telecommunication, transportation, water and wastewater lifeline systems and system components. These documents were developed in a variety of ways to achieve functionality and safety, and to address system performance and reliability. They vary considerably from system to system and represent various levels of consensus—most typically among operators, regulators, and engineering experts. Codes for interdependent systems are also starting to emerge, particularly in the interoperability of automated electrical substations and telecommunication systems.

Some commonalities and trends have emerged from this survey, which are relevant for improvements in community-scale resilience. In particular, there are gaps in codes and standards for the infrastructure systems reviewed. Codes, standards, guidelines and manuals tend to emphasize component-level rather than system-wide performance. They tend to cover minimum levels of safety or performance (e.g., for extreme loading conditions) of components as opposed to system response and levels of service. Most address day-to-day operations and do not cover the range of hazard types considered in this study, particularly the extreme, low-probability, high-consequence events.

The processes by which lifeline codes, standards, and guidelines are developed tend to be reactive and based upon past information. This may result in significant time lags before the latest information on hazards is incorporated into updates. Furthermore, some standards and guidelines have not necessarily been developed following rigorous and systematic processes.

The performance requirements within lifelines codes, standards, and guidelines focus mainly on engineering for system design and construction and operational concerns, taking into account different, but more limited sets of societal considerations. Life safety, public health, emergency response, critical service provision, property and monetary loss prevention, and environmental protection are some of the most prevalent societal considerations identified in the performance requirements established by standards and codes for lifeline systems. In particular, failures in some lifeline systems (e.g., natural gas, liquid fuel, and transportation) and some lifeline service outages (e.g., power, telecommunication (911), natural gas, water, and wastewater) that can contribute to mortality and morbidity are given the greatest emphasis in codes and standards.

For electric power, gas and liquid fuel systems, certain measures of system performance are routinely assessed and even required to be reported to regulators. These measures generally address outages during normal operations and operations and often exclude disruption caused by hazard events, which can distort the true costs and impacts of system disruption and restoration. For example, electric power providers routinely report System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI)—which generally exclude data during disruptions due to hazard events.

Most system performance measures are not directly informed directly by or linked to societal expectations, nor do they differentiate between customers or consider differential hardships imposed on society from varying durations of outage. The direct and indirect costs to customers will likely vary with the duration of system disruptions (i.e., mere inconvenience in the first few hours to severe hardship after weeks of lost service). One notable exception is the service level agreement (SLA) for telecommunication systems. SLAs establish thresholds for customer service and outages that trigger contractual penalties to the system providers. However, at present, disruptions caused by hazards such as earthquakes, hurricanes, and man-made threats are generally excluded from such agreements.

The lifeline assessments also identify a number of examples of system restoration guidelines that are generally informed by an array of societal expectations that include: public safety, mobility, business continuity, and environmental protection. System restoration times and guidelines tend to be governed by scenarios often derived from recent disaster experience or the largest disruption in the region. They may not take a robust view of the range of potential hazard types or levels of hazard severity that could affect the system.

The degree to which lifeline system codes, standards and guidelines address the provision of substitutions, temporary solutions and accessibility services (e.g., bottled water and portable toilets) for lost services also varies considerably by system. Such substitutions and temporary solutions (both within and between systems as well as those undertaken by society) can significantly affect performance outcomes and societal expectations, impacts and recovery following disruption.

Codes and standards are not the only influence on lifeline system design; factors such as voluntary measures to exceed standards, injunctions of regulatory authorities to improve performance in hazard events, and other risk management practices also influence the resilience of lifeline systems. Also noteworthy is the considerable variability in lifeline system regulation and enforcement by system, hazard, and geography (i.e., national vs. state, state-to-state, and locally). Natural gas, liquid fuel, and electric power all have regulatory data requirements focused on safety and reliability. In particular, for gas and liquid fuel pipelines, there is a nationally-consistent regulatory framework defined by federal legislation. Federal regulations also guide telecommunication systems, whereas, few states now regulate Internet-based telecommunications. However, while most US jurisdictions adopt the latest codes and standards and some even add more stringent requirements to them, other jurisdictions may not adopt them in their entirety or may reduce some requirements. Even if codes and standards are adopted, their effectiveness may be jeopardized by poor enforcement during planning, design and construction of infrastructure components. This disparity in code adoption and enforcement can have significant consequences for community resilience.

4.2 Overarching Societal Considerations

This study was challenging in part because of the almost total lack of empirical data on what members of the general public regard as acceptable lifeline performance following disruptions. Without such data, the study team had to make inferences about those expectations. Gauging societal expectations was also challenging because U.S. society is highly diverse. Expectations can vary across individuals, households, and businesses as a function of a number of factors, including: vulnerability and resilience characteristics; geographic location; hazard (including event severity, probability and duration); lifeline type; available information on the impacts of disruption; prior experience and knowledge about service disruptions; levels of resulting losses; public perceptions of the trustworthiness and competence of service providers; and the availability of substitutes and contingencies that can compensate for lifeline outages.

Public expectations and tolerances for lifeline service disruptions are dynamic and likely to be shaped by both risk perception and risk communication. Factors affecting risk perception include prior experience with hazards and lifeline outages, substitutability and dependency on lost services, and available information on the impacts of disruption. Other things being equal, disruptions may be tolerated for longer periods in severe and catastrophic events than in less serious ones, because the public will be more willing to accept that extreme hazard events are more difficult for service providers to anticipate and mitigate. Public confidence and the past performance of lifeline service providers (both during routine operations and prior hazard events) can also influence expectations and tolerances.

Public perceptions and expectations are also shaped by communications regarding the risks associated with past disasters and lifeline outages. Lifeline service providers should work with emergency management, public safety, and other governmental agencies to ensure that risk communication messages reach and are understood by the affected public. Additionally, there is evidence to suggest that societal expectations and tolerances may be changing, as social and economic activity becomes more dependent upon highly reliable service provision, particularly with regard to electric power and telecommunication systems.

Using terminology from vulnerability science and resilience research, various segments of the population and sectors of the economy are differentially exposed, differentially sensitive, and differentially adaptable to lifeline service disruptions. Because vulnerability and resilience vary as a function of exposure, sensitivity and adaptive capacity, risks associated with lifeline service disruptions are not borne equally by all members of society but are imposed disproportionately on already vulnerable social and economic groups.

One approach to assessing likely societal expectations is to look closer at how lifeline performance and disruption can have deleterious effects on what society members value most. This approach is consistent with the NIST *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, which uses Maslow's "hierarchy of needs" framework to prioritize different building and infrastructure systems in communities. For this reason, human health and safety, the functionality of health-care systems and economic well-being are priority issues that this study has focused on in exploring societal considerations regarding performance.

The NIST *Guide* also distinguishes among short-term (days), intermediate-term (weeks to months) and long-term (months to years) response and recovery needs that planning activities must take into account. While recognizing that all three time periods are important, this study has emphasized societal considerations for the short-term period and immediate impacts, disruption, and responses, again with respect to human health and the economy. The rationale for this more limiting discussion is that: (1) life safety and health are overriding values for communities, with economic activity following as a community priority since it provides the means through which a wide range of other institutions and community needs are satisfied; (2) although the consequences of lifeline disruption can cascade over time, impacts such as deaths, injuries, and business interruption losses are generally most acute during the immediate post-impact period; and (3) practically speaking, more research exists on shorter-term than on longer-term disruptions.

4.3 Lifeline Interdependencies

This study also looked critically at the interactions among different lifeline systems during normal operations as well as restoration after hazard-related events. Dependent and interdependent relationships among lifeline systems have evolved over time with various systems and technology advances expanding and linking systems together. Although they provide efficiencies and other benefits during normal operation, they also introduce unique and largely unknown behaviors in hazard-related events and system disruptions.

Because of interdependencies, some system failures can also trigger significant cascading failures and performance impacts on multiple lifeline systems, causing a number of additional direct and indirect societal impacts. The physical proximity and colocation of lifelines can provide for enhanced efficiencies but also increase societal risks for cascading failures, complex interactions in restoration, as well as risks posed by multi-hazard effects. Collocated lifelines may also require a cross-system, cross-organizational and integrated approach to planning that is difficult to implement. Within systems there can also be choke points that amplify interdependencies. Interdependencies also exist between lifeline systems and community-level processes.

Rinaldi et al. [6] offer a general classification of interdependency mechanisms as physical, geographic, cyber, and logical, emphasizing that they are not necessarily mutually exclusive. Physical interdependence exists when the performance of a given network depends on the outputs of other networks. Geographic interdependence emerges from the colocation and close proximity of systems. Cyber interdependence occurs when the interdependence between two networks is based on shared information (e.g., the "smart grid" which relies on telemetry and situational awareness data). Finally, there is logical interdependence when systems are interconnected through channels different from those previously discussed, including human decisions related to restoration prioritization among systems.

The body of research literature on interdependent critical infrastructure has grown over the past 20 years with risk assessment and system management dominating the themes of studies, followed by interdependency effects and cascading failures. Resilience-related studies of interdependent critical infrastructure are increasing but the volume of literature is still limited by comparison.

The literature emphasizes studies of electric power, water, transportation, and telecommunication systems in varying combinations. Studies involving natural gas systems and supervisory control and data acquisition (SCADA) technologies are becoming more prominent; while studies involving economic and social considerations, such as public health, have decreased in recent years. There is a distinct lack of research on cyber networks, network security and cyber interactions with other lifelines.

There is a growing body of research on system modeling pertaining to lifeline system interdependencies that can be leveraged to improve resilience across lifeline systems. However, the vast majority of lifeline interdependency studies and tools tend to focus on the technical aspects of systems and the impacts of hazards on them. More emphasis on risk reduction, system restoration, and societal impacts is needed.

There is also a lack of unified performance and restoration goals across multiple and interdependent systems. Rigorous and readily implementable theories and methods for the study of lifeline system interdependencies are similarly lacking.

The lifeline assessments developed in this study reveal a number of critical dependencies and interdependencies across lifeline systems. Virtually every lifeline system depends on electric power and telecommunications for system control and monitoring. All lifeline systems also depend on fuel and transportation, particularly for service restoration and system repairs. Fuel is a critical contingency for power when outages occur. Water is critical for cooling in the generation processes for electric power. Water also helps with pollution control, and supports other infrastructure, such as natural gas and liquid fuel systems.

The colocation of multiple systems also creates physical interdependencies that increase the likelihood that failure in one system can damage and interrupt others. Some prime examples exist with electric power and telecommunication infrastructure, and transportation elements that also serve as corridors for buried infrastructure (e.g., pipes and conduits for water, wastewater, telecommunications, power and natural gas). However, because lifeline service providers often do not share system information, many areas of physical colocation are unknown.

Some interdependencies are also increasing with time, such as the expanding role that telecommunications and electric power have in monitoring and remote control of lifeline systems, as well as household management, personal choices for renewable power, and community planning for decentralized energy.

4.4 Disaster Lessons

In general, there is a substantial body of literature on the social and economic impacts of lifeline service disruptions, spanning studies on actual events—both hazard and non-hazard related—and scenario-based and probabilistic loss projections. The lifeline assessments found great variability in both the quantity and quality of data available for lifeline systems, hazard types and severity, and across the various phases of disaster-related response and recovery. Most studies of disaster related impacts on lifeline systems are event-specific; systematic, multi-event studies are generally rare. Also, in general, there is more information and a more complete understanding of the societal impacts and restoration patterns of short-term rather than longer-term disruptions.

For electric power, most major and widespread outages have been caused by storms or other weather events. There is also more data on weather-related events than other hazards and more data on electric power outages in major hazard-related events, particularly with regard to technical aspects of component and system failure and restoration. Common information for electric power performance in hazard events includes: standard industry measures, peak number of customers without service, and time to restore service to all (or nearly all) customers.

Gas and liquid fuel production, transmission and distribution systems are susceptible to damage due to all forms of hazard events. Loss of power to oil refineries and pipeline pump stations during high wind and coastal inundation events will result in loss of production and transmission, causing a lack of fuel supply for businesses and consumers. The high concentration of fuel refineries and major transmission lines along the central Gulf Coast and Eastern seaboard results in increased exposure to hurricanes. Ground faulting and liquefaction caused by earthquakes can lead to rupture of gas and fuel pipelines, though appropriate design measures can mitigate these effects as demonstrated by the good performance of the Trans-Alaska Pipeline System during the 2002 Denali Fault earthquake.

Transportation systems are susceptible to damage or disruption during earthquakes, tsunamis and other forms of coastal inundation or riverine flooding. Common earthquake damage includes bridge failures and landslides that can hamper emergency response, particularly to remote communities. Scour induced by coastal inundation and riverine flooding can also result in bridge, rail and roadway failures. Weather events, involving wind, snow and ice, can cause disruptions but physical damage tends to be more limited. Consequently, data on transportation performance in earthquakes, tsunamis, coastal inundation and riverine flooding are more readily available.

Water and wastewater systems are also more susceptible to damage or disruptions during earthquakes, tsunamis and other forms of inundation. Disruptions to water supplies can have serious impacts on fire-fighting capacity and sanitation that can result in serious public health, safety and economic consequences. Damage to wastewater treatment systems can lead to discharge of untreated sewage into waterways and the ocean, resulting in major environmental and public health concerns. The provision of accessibility services for these two systems is also essential for community-level resilience post-disaster.

In terms of recovery timeframes, disaster experiences show that most lifeline system outages generally last from hours to weeks (short- to intermediate-term recovery). In the most severe cases, outages can last for months or years. The long-term outages are associated with the most destructive events when critical and/or multiple components of lifeline systems that are time consuming to replace, such as buildings, bridges, piping, and essential equipment, must be reconstructed or replaced to restore system operability.

4.5 Key Gaps and Deficits: Codes, Standards, Performance Requirements, and Societal Considerations

Overall, this assessment found uneven study and treatment of societal considerations in the codes and standards governing lifeline systems performance for different hazards. Lifeline codes, standards, guidelines and manuals of practice are largely associated with the performance and safe operation of components rather than system response and levels of service. Even less common are efforts to consider interoperability issues across various lifeline systems (upstream and downstream interdependencies). In a few instances, system owners or operators have established system-level performance objectives or targets for a limited number of hazards. Most guidance does not address the range of hazard types considered in this study, particularly the low-probability/high-consequence events. In general, more is known about the lifeline impacts and performance objectives for earthquakes and wind-related events than for other hazards.

Strategies to enhance resilience will invariably require difficult investment decisions in the face of limited resources. To make rational decisions, lifeline owners and operators need to consider the tradeoff between risk reduction and financial investment. Quantitative uncertainty and risk analysis therefore need to be an integral part of performance requirements and criteria. In addition, risk communication needs to be an essential part of the overall dialogue, including public messaging.

Also, there is little information on societal expectations of system performance during routine, design, and extreme hazard events for most lifeline systems. Some potential "proxies" and informants for societal expectations of lifeline performance and recovery timeframes are available, including outage reporting thresholds and criteria, post-event reviews of utility performance, regulatory changes made following disruptions, societal and economic losses, and state and local energy assurance plans. Societal expectations may also be indirectly reflected in industry practices for service restoration following outages.

Currently there is also a lack of systematic research or accepted methods for quantifying or even bounding the gap between the disaster capabilities of lifeline systems and the societal expectations of their performance. This study identified some important examples for how the gap between prescriptive performance and societal expectations can be filled, which include: community planning programs and stakeholder engagement in risk reduction planning and practices, as well as high quality system design, detailed risk assessments coupled with appropriate emergency planning, system monitoring, well-communicated emergency response procedures, and robust contingency planning and design.

4.6 Future Considerations and Trends

This study identifies a number of considerations outside its scope as well as important trends that are likely to shape future lifeline system design and performance and societal expectations. Societal expectations for lifeline system performance are changing, with decreasing societal tolerance for outages in general and lower thresholds for outage durations. Increasing interdependencies among lifeline systems, urbanization and the growing inventory of aging and deteriorating infrastructure increase the risk of system damage and disruption in future hazard-related events as well as the potential for cascading effects.

Future work both in research and applications related to community resilience needs to consider the following issues:

- Increasing social vulnerabilities due to an aging population, urbanization, and U.S. policies that are increasingly enabling disabled persons to remain in their homes where they are especially vulnerable to the loss of lifeline services;
- Economic vulnerabilities caused by the ongoing shift from a manufacturing to an information economy, growth of “cloud” based information technology, rising use of “just-in-time” strategies in inventory control and maintenance, and data storage, e-commerce and the expansion of the financial service sector, increases in telecommuting; and cost-cutting and efficiency measures in business and inventory management;
- Increasing vulnerabilities to distant lifeline disruptions caused by the continued rise of globalization, supply chains, and the interdependencies inherent in modern manufacturing and finance;
- Dependency of all lifeline systems on electric power and telecommunications for system control and monitoring;
- Increasing availability of renewable and distributed energy resources, grid modernization, decentralized power management, energy storage, and changes in the traditional structure of the electric power industry;
- Increasing physical and social vulnerability caused by the effects of climate change; and
- Lifeline system performance issues caused by theft of essential equipment (e.g., copper wire used in telecommunication systems), cyber-attacks, and other security threats.

Finally, the study cautions that unanticipated societal impacts will likely present themselves in future hazard events due to existing lifeline system vulnerabilities that remain poorly understood, absence of guidance on hazard resilient construction and installation practices, unknown and unfavorable states of repair, issues with system functional capacity, and ongoing changes in technology.

5. Recommendations

Recommendations resulting from this study are organized to identify the needs associated with: (a) codes, standards, and guidelines; (b) research; (c) modeling; and (d) systems operations. These needs target lifeline operators, practitioners, regulators, and researchers concerned about societal considerations in hazard-related system performance and potentially involved in lifelines standards and code development related activities. The following set of overarching recommendations was derived from the individual assessments of the study team. They were then discussed and prioritized with the Project Review Panel. All recommendations shown below were deemed high priority. Additional recommendations are provided in Chapters 2 through 8 of the NIST GCR 16-917-39 Report, *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*.

5.1 Codes, Standards, and Guidelines

This study revealed critical gaps in the codes, standards, and guidelines that govern the design, construction, operation, and performance of various lifeline systems and system components. Ten recommendations are offered to address needs related to lifeline codes, standards, and guidelines. The priority rankings reflect organizational and framework needs, available information, new knowledge needs, guidelines and standards development needs, and scoping breadth, with recommendations that pertain to broad issues and improving community resilience considered higher priorities than recommendations for specific lifelines.

- A1. Identify or establish an organization and process for advocating, harmonizing and unifying the consensus procedures for lifeline guidelines and standards development.
- A2. Develop more consistent terminology for lifeline standards.
- A3. Develop an up-to-date and complete suite of codes, standards, and guidelines for all lifeline systems to reflect the current state of practice, knowledge, and performance requirements.
- A4. Develop a methodology to combine component-based design criteria into system level performance targets.
- A5. Develop lifeline system performance requirements that relate to community resilience and better reflect societal considerations.
- A6. Develop consensus-based guidelines and standards for the design of new lifelines and the retrofit of existing lifelines that reflect community resilience performance requirements and societal considerations.
- A7. Develop guidelines to inform the design, interoperability, and upkeep of lifeline system dependencies.
- A8. Reduce inconsistencies in the compendium of codes and standards that guide design, construction and resilience of the built environment, such as fire codes, building codes, and lifelines codes, standards, and guidelines.
- A9. Develop consistent policy and standards on accessing information and databases about critical infrastructure systems that is coordinated with Department of Homeland Security critical infrastructure activities.
- A10. Provide updated guidance for evaluating gas and liquid fuel pipeline and facility response to seismic hazards, floods, coastal storms, and tsunami-related inundation.

5.2 Research

The study identified a number of gaps in data and knowledge necessary to improve the fundamental understanding of acceptable lifeline performance. Fifteen recommendations with respect to systematic study and research needs are offered. All are considered high priority, with those encompassing all lifelines and broader topics listed before those related to only one lifeline.

- B1. Gather information on and systematically study the relationships between service disruptions, and societal impacts and expectations to better understand lifeline system performance.
- B2. Develop and conduct a targeted research program to assess societal expectations associated with lifeline system performance.
- B3. Systematically study and compare the array of design approaches and methods for addressing societally-based performance requirements within current codes, standards and guidelines for lifeline systems.
- B4. Investigate the differential vulnerability among social groups to lifeline system outages.

B5. Systematically collect and review various "proxies" and secondary evidence for societal expectations of lifeline performance and restoration timeframes.

B6. Assess the various lifeline performance programs and practices for public safety and develop guidance on their application to other critical lifelines, including multiple, interdependent systems and collocated facilities.

B7. Conduct research on needed service restoration times, including how system operability as a performance metric supports community resilience.

B8. Study lifeline system operator organizational issues and how they affect community-scale lifeline performance and resilience planning.

B9. Enhance the understanding of infrastructure-related failures and cascading effects resulting from low-probability/high-consequence events.

B10. Develop post-event data collection protocols to assess lifeline system recovery and restoration timeframes and improve the understanding of restoration processes across individual and interdependent lifeline systems.

B11. Develop tools to identify interdependent infrastructure systems and services along with their restoration criteria.

B12. Establish procedures to quantify hazards for spatially distributed systems.

B13. Enhance the understanding of lifeline system supply sources and end-point facilities and their role in system performance, restoration, and community and regional recovery with the goal of improving databases and modeling of such sources and facilities.

B14. Perform studies on changes in water demand considering an array of hazards as well as seasonal and longer-term climate variability, like drought.

B15. Improve knowledge, databases and modeling for the impact of widespread flooding and storm damage on regional fuel supplies.

5.3 Modeling

There is a growing body of system modeling for lifeline systems and their interdependencies that can be leveraged to improve resilience across lifeline systems, but there are also notable limitations in scope, outputs, integration, and validation that need to be addressed. Three modeling related recommendations are offered. All are considered high priority.

C1. Aggregate the existing suite of infrastructure modeling tools and create a user-friendly interface so communities can properly assess their lifeline-related system performance and restoration risks, including uncertainty.

C2. Develop first-generation models and practical tools to analyze community resilience that account for lifeline system dependencies and interdependencies.

C3. Improve numerical modeling of lifeline systems, with emphasis on validation of models, developing the most effective simulation procedures, and applications in real systems.

5.4 Lifeline System Operations

The study also identifies a number of needs related to lifeline system operations and operational design. These too must be addressed to improve community resilience and bridge the gap between the post-event capabilities of lifeline systems and the societal expectations of their performance and restoration. Five recommendations are offered. All are considered high priority.

D1. Develop a process for major utilities to conduct self-assessments of their preparedness for various natural hazard events, as a basis for prioritizing improvement to system robustness and post-event response.

D2. Develop guidance for lifeline service providers on how to engage and collaborate with communities, including emergency management agencies and other key community institutions, in developing resilience strategies and preparing system restoration and contingency plans.

D3. Develop guidance for local planning (e.g., for fuel delivery to emergency responders and critical infrastructure).

D4. Develop guidance for lifeline service providers to evaluate the effects of system component failures, both in isolation and in combination, and considering upstream and downstream dependencies.

D5. Design protocols for lifeline service providers, working with emergency management and other community institutions, to communicate to the public the likely impacts of different hazard events on service provision and disruption.

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