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The National Institute of Standards and Technology's Impact on Fire Safety Standards

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The National Institute of Standards and Technology's Impact on Fire Safety Standards

BENJAMIN M. MILLER, TOM LATOURRETTE, DRAKE WARREN, DAVID METZ

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About This Report

Standards provide critical benefits across a wide variety of contexts, including safety and health, environmental protection, and quality of products and services. However, while these benefits are generally acknowledged, estimating the social and economic value of standards and determining how specific entities and activities influence their development require careful analysis. In October of 2018, the National Institute of Standards and Technology (NIST) asked the RAND Corporation to estimate the benefit of NIST's research contributing to particular fire safety standards. The original objectives of the project were to (1) document the role of the NIST in the standards development process, (2) estimate the value these standards provide to society, and (3) thereby inform the economic value of NIST's contribution to these standards. This report presents results for the first two objectives. Given that NIST's contribution is one of several inputs combining to create these standards, NIST's share of the credit for their value could not be quantified. Our analysis focused on case studies in standards for home smoke alarms and for protecting structures at the wildland-urban interface (WUI). Our analysis draws on a wide variety of qualitative and quantitative methods to holistically describe the impacts of these standards and NIST's role in their development.

The intended audience of this report includes those who work on fire safety research, fire safety standards, building codes, and technology transfer. The conclusions presented here may also be of interest for broader resource allocation and federal budget justification purposes. Finally, this report was written to be accessible to any interested members of the general public.

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Summary

Standards play an important role in health and safety of everyday life, affecting everything from food production and transportation services to building design and consumer products of all types. Standards help ensure that goods and services traded in national and global marketplaces are both safe and effective. Without effectively implemented standards, the world would be a much more hazardous place to live in. The National Institute of Standards and Technology (NIST) is the U.S. government's primary agency for shaping and influencing the development of measurement standards, both nationally and internationally, and plays a unique and critical role in the development of measurement standards.

While the safety and health benefits of standards are generally acknowledged, our understanding of their value, how they accrue, and what entities and activities are responsible for creating them is limited. In October of 2018, NIST asked RAND to estimate the benefit of NIST's research contributing to particular fire safety standards. The original objectives of the project were to (1) document the role of the NIST in the standards development process, (2) estimate the value these standards provide to society, and (3) thereby inform the economic value of NIST's contribution to these standards. This report presents results for the first two objectives. Given that NIST's contribution is one of several inputs combining to create these standards, NIST's share of the credit for their value could not be quantified.

Our analysis focused on case studies in standards for home smoke alarms and for protecting structures at the wildland-urban interface (WUI), the transition areas between wildlands and urban spaces. We demonstrate NIST's role in standard development through three case studies, selected in coordination with staff of NIST's Fire Research Division: historical work that led to the initial adoption of smoke alarms, ongoing changes to smoke alarm performance requirements, and ongoing research on wildfire safety in WUI. We then conduct novel analyses to indirectly estimate the potential impacts of smoke alarm and WUI standards.

Our analysis compiles many different sources of information, including reviews of research literature, interviews with representatives of NIST laboratories and standards development organizations (SDOs), review of SDO documentation of the standards development process for several standards and codes, observation of an SDO meeting, a survey of research staff in the NIST Fire Research Division, a novel module on smoke alarm usage in a national representative survey, analysis of the relationship between state building codes and fire safety outcomes, and analysis of data from the 2018 Camp Fire in Paradise, California.

Our study shows that NIST's role in standards development comes at the very beginning of the process, providing the foundational research on which subsequent activities are built. NIST researchers and staff proactively and intentionally engage with a variety of SDOs, and these

SDOs in turn deeply value NIST's participation. This report highlights multiple examples where research conducted by NIST proved to be essential to developing effective standards.

Smoke Alarm Standards

NIST research played a critical role from the late 1960s through the late 1970s in rapidly shifting home smoke alarms from novelty to standard practice. Data from several early demonstration projects in which NIST participated showed benefits from installation of smoke alarms. In addition to promoting the inclusion of smoke alarms in homes, NIST's work also helped advance the effectiveness of smoke alarm technology, which led to a number of design improvements and specifications and ultimately to the first smoke alarm standard in 1974.

Since the mid-1970s, the use of smoke alarms in homes has grown substantially, largely facilitated by the adoption of state and local ordinances requiring their use. Following this early period, NIST continued to support the development of smoke alarm standards with work targeted at specific aspects of smoke alarm placement and performance. One area of research focused on revisiting smoke alarm design and testing in light of the shift to the use of largely synthetic materials in upholstered furniture versus natural furnishing materials for which early smoke alarm designs had been developed. A major outcome of this research included updates to test performance requirements reflecting conditions created in fires of modern synthetic furnishing materials.

Another aspect of this later research focused on reducing nuisance alarms, primarily stemming from cooking aerosols and bathroom shower mist. Nuisance alarms were an important area of investigation because the inconvenience often led home occupants to disable smoke alarms, thereby leaving occupants unprotected and contributing to deaths associated with residential fires. Since the late 1980s, residential smoke alarm standards have evolved as a result of NIST's contributions and reflect changes in restrictions on smoke alarm placement and technology. Most recently, NIST research endeavored to resolve nuisance alarms independent of location or technology, which has motivated a 2020 revision to smoke alarm standards to adopt this newest capability.

Prior to examining the benefit of smoke alarm standards, we compiled and summarized research on the effectiveness of smoke alarm technology. This body of research shows that the presence of a working smoke alarm in a home reduces the number of fires per home, the number of reported fires per fire, and the number of fatalities per reported fire, combining to result in the risk of a fire fatality in a home with a smoke alarm being 7 to 26 times lower than in a home without a smoke alarm.

To measure the social and economic impact of smoke alarm standards, we developed a novel database documenting state-level variation in the adoption of smoke alarm standards in residential housing codes. We found that the frequency with which states update residential building codes can vary significantly, although we did not find evidence that adopting codes

containing the most recent smoke alarm standards significantly alters the number or severity of fires nor the number of injuries or fatalities. We suspect this is because the largest gains in fire safety from smoke alarms occurred prior to 2003, which is the earliest point in time we can measure these correlations. In fact, by 2003, 95 percent of households had already installed at least one smoke alarm. As a result, safety impacts imparted through the adoption of updated residential smoke alarm standards since 2003 have been too small to measure.

These results do not necessarily mean that further updates to smoke alarm standards or building codes are irrelevant. Ongoing work on smoke alarm standards, supported by NIST research, continues to address nuisance alarms, as well as testing requirements, system interconnection, notifications targeting children, and other topics. A nationally representative survey of American households conducted by RAND in March 2020 found that 36 percent of households reported having disabled a smoke alarm (e.g., by removing the batteries) to prevent nuisance alarms, which is an issue that current standards development efforts are seeking to address. To the extent that new standards, based in part on NIST research, can reduce the frequency with which households disable smoke alarms, that would provide meaningful improvements in fire safety and general well-being.

Wildland-Urban Interface Standards

As the risk of WUI fires has increased, the research community has begun paying increased attention to wildland fires, which have grown in number and intensity and are causing more damage and taking more lives. The increase in WUI risks is driven by increased human-caused ignition and increased building exposure. The large wildland fires that occurred in the 1990s and early 2000s appear to have motivated NIST's work in this area (e.g., see Manzello, Cleary, and Yang, 2004), which began as an extension of its general fire efforts at the National Fire Research Laboratory.

According to NIST personnel, early WUI fire research conducted by NIST focused on developing a better understanding of how fire spreads from the vegetative fuels of the wildland to structures. By 2004, this research had evolved to an examination of firebrands—small flaming or glowing embers that may be transported by the wind into a building's vents or crevices and cause structure ignition. NIST's research demonstrated that a majority of structure ignitions were in fact caused by firebrands rather than flame contact or thermal radiation and continuing research is examining gaps in knowledge about firebrands. NIST has also collected data on historic fires to further study of fire behavior and consequences. Other complementary research has examined the socio-technical aspects of WUI risk.

NIST's work is providing fundamental groundwork needed to develop evidence-based WUI standards and influence study of different building designs and materials to deter firebrand-driven ignition. NIST also provided technical support and leadership in the

development and implementation of Executive Order (EO) 13,728, Wildland-Urban Interface Federal Risk Mitigation (Obama, 2016).

Research into the effectiveness of design changes is still in its early stages, so the effects of potential design changes on survivability are highly uncertain. To measure the social and economic impact of WUI standards, we conducted a geospatial analysis of the extent to which homes built with newer construction methods avoided damage or destruction during the 2018 Camp Fire in Paradise, California. Our results suggest that the survivability of houses has generally been improving over time. This result is consistent with steady improvements in standards and the associated changes in building practices, although other explanations are also possible.

We used two different approaches to estimate the savings that might occur if all houses within the 2018 Camp Fire perimeter were as survivable as houses built in 2000 to 2009 (the decade in which houses built had the lowest damage rates). Results of the two approaches indicated a 6- and 43-percent reduction in housing losses, respectively, which we estimated to be equivalent to \$600 million or \$4 billion in averted losses.

Although we did find a general relationship between evolving standards and reduced damage in residential homes, limitations in data meant we were unable to link these improvements to a specific change in building codes. Studies of buildings affected by wildfires typically collect minimal information on undamaged buildings, making it impossible to compare the design of buildings that ignited with those that survived. Collection of such data could greatly improve our understanding of the factors that increase survivability in wildfires, which would lead to the development of improved WUI standards and building codes.

Conclusion

The development and adoption of standards and codes involve a number of different stakeholder groups, sometimes with competing interests. Standard development requires basic research, development of standardized testing methods, and the coordination and integration of stakeholder needs. Adoption further requires widespread incorporation of standards into codes and enforcement of those codes. Because of the collaborative and multistage nature of this process, the economic and social impacts of both the standards themselves and the specific contributions of particular entities toward the development of those standards are difficult to isolate. In addition, in the case of standards that apply to infrastructure, such as those for fire safety, it can take years to decades for the benefits of research to make their way into the built environment and be realized.

Our analysis identified a number of important contributions from NIST to the development and adoption of standards for smoke alarms and WUI protection. While our quantitative analyses were not able to detect significant economic benefits that can be linked directly to specific standards, this in no way suggests that fire safety standards, and NIST's contributions to them,

do not have great value. In the case of smoke alarms, the most significant gains were likely made prior to the time period for which we conducted our analysis. Conversely, in the WUI setting, standards are still in the active research stages, and the biggest benefits are likely yet to be realized. In both cases, we discuss clear evidence of steady safety improvements over time and suggest that those steady improvements may be largely or partly attributed to the concurrent evolution of multiple related standards. Standards may also have indirect economic benefits, such as increasing technology development and adoption and efficiency of markets, which our analyses also cannot capture.

The type of foundational research conducted by NIST is a necessary precursor to the development of standards that yield meaningful public health and safety benefits. Further, although other entities devoted to fire safety research exist, substitutes to NIST are not readily apparent. Thus, while we cannot know if another entity would have made the contributions to smoke alarm and wildfire safety standards that NIST did, it is clear that NIST's leadership role in basic research and standards development has been critical for bringing the standards and their adoption to their current status.

Acknowledgments

This report was made possible due to the generosity of a large number of individuals. Countless NIST staff were generous in sharing their time and first-hand perspectives. In particular, we thank Kathleen McTigue, Eric Puskar, Mike Walsh, Tom Cleary, Sam Manzello, Stanley Gilbert, and all the staff at the NIST's Fire Research Division for their support throughout this project. The Fire Research Division met with us on multiple occasions, hosted our presentations, were extremely responsive to the survey we present in Chapter 2, and were always thoughtful and intentional about connecting their research to needs through standards rather than simply conducting research for its own sake. Many representatives from standards development and other organizations were similarly generous, including Tom O'Toole and Dan Smith of ASTM International; Debra Ballen, Anne Cope, Daniel Gorham, Faraz Hedayati, Sherry Melton, Murray Morrison of the Insurance Institute for Business & Home Safety® (IBHS); Karl Fippinger, Gabriel Master, Mike Pfeiffer, and Sara Yerkes of the International Code Council (ICC); Kathleen Almand and Guy Colonna of the National Fire Protection Association (NFPA); and David Mills and Diane Haithcock of Underwriters Laboratories. Cory Ogle, Richard Roux, and the members of NFPA's Single- and Multiple-Station Alarms and Household Fire Alarm Systems (SIG-HOU) Technical Committee were kind enough to allow us to observe their meeting in July 2019 in Indianapolis.

Several of our analyses benefited greatly from those who provided us with data and other analytic materials. We thank Kathleen Carter at the U.S. Fire Administration (USFA) for the providing the National Fire Incident Reporting System (NFIRS) data at truly astounding speed. We again find ourselves thanking NIST staff, David Butry and Douglas Thomas, who shared code and insights from their work, which served as an inspiration for our approach to weighting NFIRS responses. On the WUI side, we are similarly indebted to Dale Kasler and Phillip Reese of the *Sacramento Bee*, who saved us immense time and effort by providing us with the Camp Fire data they assembled for their analysis. David Shew also provided critical insights and perspective on WUI issues in California.

At RAND, Eric Landree provided helpful perspective on NIST structure and processes, and Barbara Bicksler was invaluable in helping condense our analysis into a clear and organized narrative. Finally, we thank our peer reviewers, Stephen Quarles and Lloyd Dixon, for their very helpful insights and perspectives.

Abbreviations

ALP	American Life Panel
ANSI	American National Standards Institute
BCEGS	Building Code Effectiveness Grading Schedule
CAL FIRE	California Department of Forestry and Fire Protection
CDC	Centers for Disease Control and Prevention
DINS	Damage Inspection (CAL FIRE program)
EO	Executive order
FCIC	Fire, Performance, Wildland-Urban Interface Code Interpretation Committee
FDID	Fire Department ID
FY	fiscal year
HUD	U.S. Department of Housing and Urban Development
IBHS	Insurance Institute for Business & Home Safety
ICBO	International Council of Building Officials
ICC	International Code Council
IFCI	International Fire Code Institute
ISO	International Standards Organization
IWUIC	International Wildland-Urban Interface Code
NBS	National Bureau of Standards
NFIRS	National Fire Incident Report System
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
OMB	Office of Management and Budget
R/T	research/testing
SDO	standards development organization
TC	technical committee

TG	task group
USFA	U.S. Fire Administration
VCS	voluntary consensus standard
WG	working group
WUI	wildland-urban interface

1. Introduction

In 1901, Congress founded the federal government’s first physical science research laboratory, the National Bureau of Standards (NBS), as a measurement and standards laboratory within the U.S. Department of the Treasury, although it was quickly moved to the new U.S. Department of Commerce and Labor. When the Department of Commerce and Labor was split in 1913, NBS was retained by the new Department of Commerce. The agency has not moved since that time, although in 1988 NBS was renamed the National Institute of Standards and Technology (NIST).¹ NIST’s mission is “to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life” (NIST, 2021).

NIST’s mission establishes it as the U.S. government’s primary agency for shaping and influencing the development of measurement standards, both nationally and internationally. As evidenced in this report, NIST plays a unique and critical role in the development of measurement standards.

The Purpose and Scope of This Report

In October of 2018, NIST asked RAND to estimate the benefit of NIST’s research contributing to particular fire safety standards. The original objectives of the project were to (1) document the role of the NIST in the standards development process, (2) estimate the value these standards provide to society, and (3) thereby inform the economic value of NIST’s contribution to these standards. This report presents results for the first two objectives. Given that NIST’s contribution is one of several inputs combining to create these standards, NIST’s share of the credit for their value could not be quantified.

RAND proposed fire safety standards as the broad technology area due to the increasing prevalence of wildfire losses and the tangible outcomes of fire safety research. In this report we demonstrate NIST’s role in standard development through three case studies, selected in coordination with staff of NIST’s Fire Research Division: historical work that led to the initial adoption of smoke alarms, ongoing changes to smoke alarm performance requirements, and ongoing research on wildfire safety in the wildland-urban interface (WUI), the transitional area between wildland and urban space. We then separately conducted two novel analyses to indirectly estimate the potential impacts of smoke alarm and WUI standards. A comprehensive analysis of the value of NIST’s contributions would account for the costs of NIST’s research

¹ For the remainder of the report, NIST is used to refer to both NIST and NBS.

investment. However, because the benefits of fire safety standards flow from a number of sources beyond NIST's contributions, it is not feasible to estimate the total investment cost that led to those benefits.

To conduct these evaluations, we compiled many different sources of information, including reviews of research literature, interviews with representatives of NIST laboratories and standards development organizations (SDOs), review of SDO documentation of the standards development process for several standards and codes, and observation of an SDO meeting. We also conducted a survey of research staff in the NIST Fire Research Division, developed a novel module on smoke alarm usage in a national representative survey, and conducted analyses of the relationship between state building codes and fire safety outcomes and of data from the 2018 Camp Fire in Paradise, California.

The Purpose of Standards

Standards influence almost every aspect of day-to-day life. Standards affect food production, transportation services, building design, and consumer products and services of all types. For more than a century, national and international SDOs have been developing detailed specifications and conditions to guide the production of goods and delivery of services. One purpose of these standards is to ensure that the goods and services traded in national and global marketplaces are both safe and effective. For example, standards help ensure that food is safe to eat and that children's clothing does not easily catch fire.

Another purpose of standards is to support functional and efficient national and international commerce. NIST was founded at the behest of not only scientists but also manufacturers and makers of electrical instruments to address severe social and economic challenges created by the lack of national standards.² At the beginning of the twentieth century, when NIST was founded, few national standards for measuring or producing products existed. What standards did exist were local or regional and thereby created confusion for interstate commerce and challenges for activities that are often taken for granted today, such as conducting fair transactions and fitting together parts. "There were [for example] at least eight different gallons and four different feet in use" (NIST, undated). Some of NIST's first actions were to develop standards for measuring length, light, and time.

In some cases, businesses actively encourage making certain standards mandatory in order to ensure all members of an industry are following the same rules and to gain legal support in ensuring the industry as a whole is safe and efficient. For this reason, leadership in standards

² An Office of Standard Weights and Measures already existed as part of the U.S. Department of the Treasury, "but the office had few employees, and some people disliked the idea of the federal government imposing standards or anything else on industry" (NIST, 2017a).

development conveys a large economic advantage. If a nation's standards, laws, and regulations become the basis for other nations' standards, laws, and regulations, then it is much easier to sell goods and services on the global market (Miller et al., 2017).

The Standards Development Process

Multiple types of standards serve different functions (Mackay, 1989), including best practices, guidelines, specifications, performance measures, test methods, and codes. Consequently, what is considered to be a "standard" varies across stakeholders and communities of interest. The Office of Management and Budget Circular No. A-119 (OMB, 2016, p. 15) defines a standard as a "common and repeated use of rules, conditions, guidelines or characteristics for products or related processes and production methods, and related management systems practices."

While NIST develops standard reference materials internally, in general its research in the development of standards supports the development of voluntary consensus standards (VCSs) by external, nongovernmental SDOs. Circular No. A-119 (OMB, 2016, p. 16) defines VCSs as "a type of standard developed or adopted by voluntary consensus standards bodies, through the use of a voluntary consensus standards development process." U.S. federal government policy outlined in Circular A-119 encourages federal agencies to actively participate in the VCS development process.

A large number of SDOs develop VCSs, and these standards often build upon one another as they are developed. Some testing standards focus on the methods for conducting tests and constructing the equipment needed for those tests. Other design standards specify the conditions or criteria that certain products or services should meet, referencing testing standards for measuring whether the design standard's conditions or criteria were met. For example, a design standard requiring product materials to be flame resistant may reference a testing standard for determining flame resistance.

The Role of Standards Development Organizations

SDOs are critical to the development of voluntary standards. They serve as curators and managers of voluntary standards within their scope of influence. They also manage the process of developing new consensus standards or modifying existing standards, which includes soliciting proposed changes, managing voting membership, convening meetings to debate and adjudicate proposed changes, and publishing updated standards for their stakeholders and industry partners. Some SDOs have narrowly defined scopes, such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, while other organizations, such as ASTM International or the International Organization for Standardization (ISO), may manage and promulgate standards that transcend multiple industry sectors.

Although each SDO operates slightly differently, they all develop standards via a democratic consensus process using committees composed of individuals from multiple groups such as researchers, manufacturers, users, government entities, and other groups involved in a given

topic. All prominent SDOs are themselves accredited by the American National Standards Institute (ANSI), which requires that SDOs meet ANSI’s “requirements for openness, balance, consensus, and due process and adhere to ANSI’s neutral oversight, assuring that all interested parties have an opportunity to participate in a standard’s development” (ANSI, undated).

Although VCSs are by definition voluntary, many organizations and industries commit to following them to maintain quality, competitiveness, and efficiency. In some cases VCSs are adopted internationally. In addition, VCSs are often incorporated into government regulations such as building codes or other legal instruments, thus shifting a voluntary standard to a mandatory requirement with legal enforcement. The ways in which VCSs make their way into codes and regulations vary, but a common route is through model codes. SDOs, such as the National Fire Protection Association (NFPA) or International Code Council (ICC), develop model building and fire codes through a consensus process. States, counties, townships, and/or municipalities typically select portions of a model code and adopt those provisions.³ Once an authority having jurisdiction adopts portions of a model code and it is incorporated into law or regulation, those provisions become mandatory.

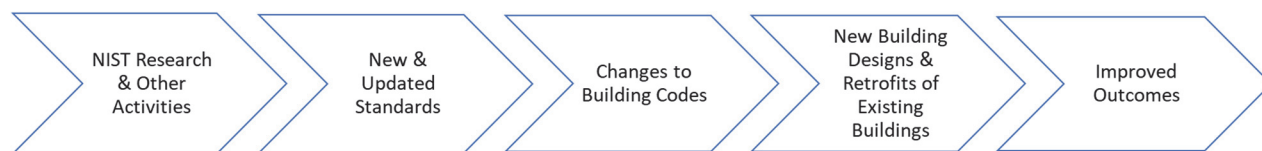
How National Institute of Standards and Technology Research Contributes to Social Benefits

Much of NIST’s work involves fundamental research into and development of “infratechnologies,” which are “fundamental measurement standards, measurement and test methods, science and engineering data bases, process models, and the technical bases for interface standards” (Tassey, 1999, pp. 113–114). Infratechnologies developed by NIST enable downstream impacts, such as improvements to codes and standards, as shown in the generic logic model in Figure 1.1. Working from left to right in the figure, one can see how NIST research and development activities can lead to changes in standards and codes, which, when adopted, can lead to beneficial impacts on society, such as reductions in property damage and personal injuries. Standards may also provide indirect benefits, such as increasing technology development and adoption and efficiency of markets. These indirect benefits are not captured in Figure 1.1 or in our analyses.

While NIST is a key player in conducting research and development related to new and improving existing standards and is the U.S. government’s primary voice in the development of measurement standards, many other organizations are also involved in the development of standards. Industry’s knowledge of manufacturing processes as well as their knowledge of how their products and services are typically affected by standards make them key members of the

³ Organizations rarely adopt a model code in its entirety. For example, the state of Florida would not normally adopt snow-loading provisions in its building code since snow is not usually an issue in Florida. North Dakota would not typically adopt hurricane provisions in its building code since hurricanes do not usually occur in North Dakota.

Figure 1.1. High-Level Logic Model of How National Institute of Standards and Technology Activities Lead to Economic Impacts



standards development process as well. Other federal government agencies, as well as state and local government entities, often provide subject matter expertise or technical knowledge on standards related to their mission or function. Academic institutions contribute to standards development through research and development activities. NIST collaborates with all of these entities. It is through their collective effort that development, promulgation, and consistent, incremental improvement of standards contribute to the competitiveness of U.S. manufacturers and lead to better products and services that contribute to quality of life.

Standards and codes relating to buildings, such as the fire safety standards examined in this report, are generally mandatory only for new construction. Except in unusual cases where local codes specifically require compliance when retrofitting or remodeling, the implementation of standard and code requirements only propagate into the community at the pace of infrastructure growth or replacement. Given the long lifetime of building stock, it can take decades for the economic and social benefits of new building standards and codes to be realized.

Although this report focuses on fire safety standards, it is important to realize that NIST researchers and staff are engaged in a wide range of activities across a diverse set of standards and standards-setting organizations. NIST also represents the United States in the development of international standards, promoting a safe, fair, and effective global marketplace. A summary of the impact of NIST's work in a wide variety of other areas is available on NIST's website (NIST, 2018b).

Organization of This Report

The remainder of this report proceeds as follows. Chapter 2 discusses NIST's role in the development of fire safety standards generally. Chapter 3 discusses NIST's role in the development of smoke alarm standards; for temporal and contextual clarity this chapter includes both the historic and ongoing case studies of smoke alarm standards. Chapter 4 presents a quantitative analysis of how the adoption of smoke alarm standards into building codes has affected the number and severity of fires, injuries, and fatalities. Similarly, Chapter 5 presents the case study of NIST's role in the ongoing development of WUI standards. Chapter 6 presents the quantitative evidence on the potential benefits of WUI standards. Chapter 7 concludes with a brief reflection on NIST's role in contributing to societal benefits.

2. The National Institute of Standards and Technology's Role in the Development of Fire Safety Standards

NIST's fire research purportedly began in 1904, "when a pile of leaves on the Bureau grounds ignited and it was soon discovered that fire hoses from the different buildings could not be coupled together" (Gross, 1991, p. 119).⁴ Foreshadowing its continued standard-based approach for addressing fire safety challenges, NIST worked with NFPA to create a national standard for coupling hoses and fire hydrants. In 1914, a Fire Resistance section was established within NIST's Heat Division, and the research conducted by this small team provided the underlying basis for some building codes.

During its early decades of fire research, this team investigated such topics as the behavior of building support beams during fires, materials and equipment on ships, and the self-ignition properties of materials ranging from flammable liquids to photographic film. Their work expanded to research supporting voluntary standards for flammable fabrics in uses ranging from circus tents to children's apparel.⁵ NIST provided standards testing services for government agencies, as well as to commercial industry groups in the 1950s, when the sole commercial laboratory—UL—became overloaded with requests.

Throughout NIST's research efforts, impacts on fire safety standards were not serendipitous but rather a focused outreach effort:

It is worth noting that NBS staff have actively participated in national standardization organizations, notably NFPA and ASTM, from the beginning. There have also been contacts, cooperation and participation through the years with research and standardization organizations world-wide, including the British Fire Prevention Committee (as early as 1915), ISO [International Standards Organization], CIB [International Council for Research and Innovation in Building and Construction], Combustion Institute, IAFSS [International Association for Fire Safety Science], and the many other national and international organizations involved in fire research, testing and standardization. (Gross, 1991, p. 124)

National Institute of Standards and Technology Fire Research Division

Until about 1935, fire research at NIST was funded using less than 1 percent of NIST's overall appropriation and through special programs sponsored by other agencies or industry. Funding grew after that time, and fire-focused sections were established within NIST. NIST's

⁴ Much of the historical information in this paragraph and the subsequent paragraph comes from Gross (1991).

⁵ The Fabric Flammability Section at NIST was responsible for supporting the Flammable Fabrics Act of 1953, until the 1972 Consumer Products Safety Act transferred this responsibility to the newly created Consumer Products Safety Commission.

overall fire research effort was housed within the Building Research Division until major changes were implemented by the Fire Research and Safety Act of 1968 (Gross, 1991; Wright, 2003). This act expanded fire research, education, and training programs at NIST and also established the National Commission on Fire Prevention and Control. In 1973, the commission published its famous report, *America Burning*, which included several recommendations related to expanding fire research at NIST.⁶ The report spurred passage of the Federal Fire Prevention and Control Act of 1974, which provided separate congressional appropriations of up to \$3.5 million for fiscal year (FY) 1975 and \$4 million for FY 1976 for a new NIST Center for Fire Research. This center initially consisted of two divisions: the Fire Science Division and the Fire Safety Engineering Division (Wright, 2003). The division structure was reorganized several times until the divisions were merged in 2000 into the single Fire Research Division that exists today.⁷

Today, NIST continues to play a key role in the standards development process to reduce the risk of fire in buildings and communities. NIST's Fire Research Division has developed a road map (Hamins et al., 2012) that includes the Fire Research Division's approach to supporting the development of standards and codes. The document includes a strategic vision that identifies key codes, standards, and broader SDO committees that should be developed or supported in order to achieve the Fire Research Division's broader fire safety goals.⁸ The *Strategic Roadmap* (Hamins et al., 2012) notes that research can be translated to changes in code both through service on committees as well as through presentations to committees. The document also highlights the need to engage beyond the code and standards development process to collaborate with regulators and industry.

⁶ Indeed, NIST had proactively established a separate Office of Fire Programs in 1972 in anticipation of requests that would stem from the commission's report (Gross, 1991).

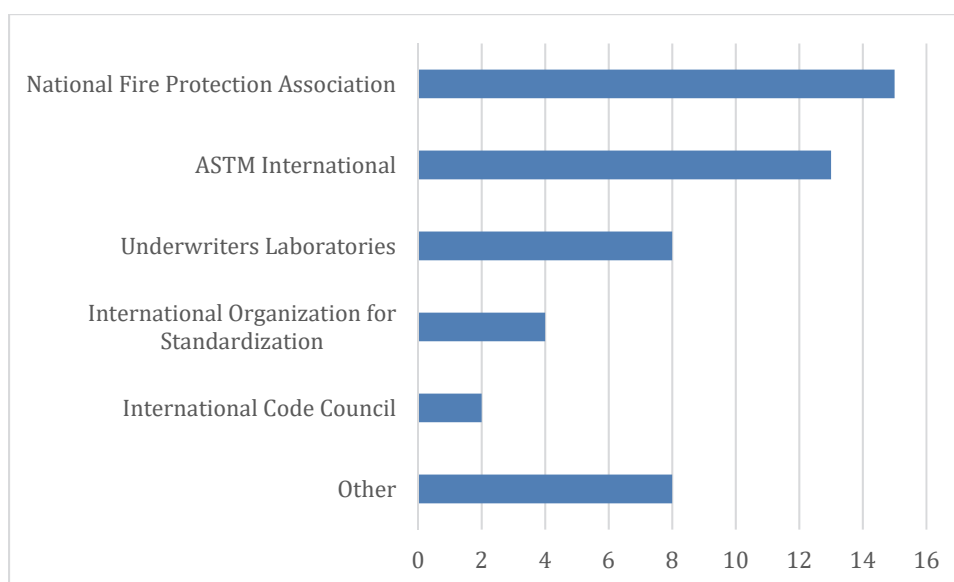
⁷ The Fire Research Division first appeared in 1981 following NIST organizational changes, although it was one of several divisions within the Center for Fire Research at the time (Wright, 2003). Today, NIST's Fire Research Division is composed of five research groups: Engineered Fire Safety Group, Fire Fighting Technology Group, Flammability Reduction Group, Wildland-Urban Interface Fire Group, and the National Fire Research Laboratory. The Fire Research Division also includes two NIST programs, the Fire Risk Reduction in Buildings Program and the Fire Risk Reduction in Communities Program.

⁸ Of particular relevance to the case studies discussed later in this report, the road map identifies UL 217 (Smoke Detectors and Alarms) and NFPA 72 (2019a) (National Fire Alarm and Signaling Code) as critical committees on smoke alarms. For WUI, three items are identified as in need of stage 1 measurement science. The first is work occurring under ASTM E05.14, including "new standards on firebrand penetration of vents; firebrand ignition of roofing, siding, window glazing, and decks; window vulnerability to firebrand assault" (Hamins et al., 2012). The second is replacing or improving test methods for buildings exposed to WUI fires, in support of the ICC's WUI Building Code, which currently cites ASTM E119 (ASTM, undated b), UL 263, ASTM E1354 (ASTM, undated c), and FM4470. Third is the California State Building Code Chapter 7A (State Fire Marshal, 2007), which requires "improved standards for materials and construction methods for building exteriors exposed to wildfire" (Hamins et al., 2012).

Involvement in Standards Development Organizations

To better understand how researchers in the Fire Research Division engage with standards development organizations, RAND surveyed the 42 researchers in the division in September 2019.⁹ (Survey details are available in Appendix A.) Twenty-four of the 29 respondents reported some level of involvement with an SDO over the course of their career at NIST, and 14 reported involvement in more than one SDO. Figure 2.1 shows the involvement of NIST researchers across prominent SDOs for fire safety standards. These researchers are most commonly involved with NFPA, ASTM International, and Underwriters Laboratories.

Figure 2.1. Standards Development Organizations' Involvement Among Current Researchers in the National Institute of Standards and Technology's Fire Research Division



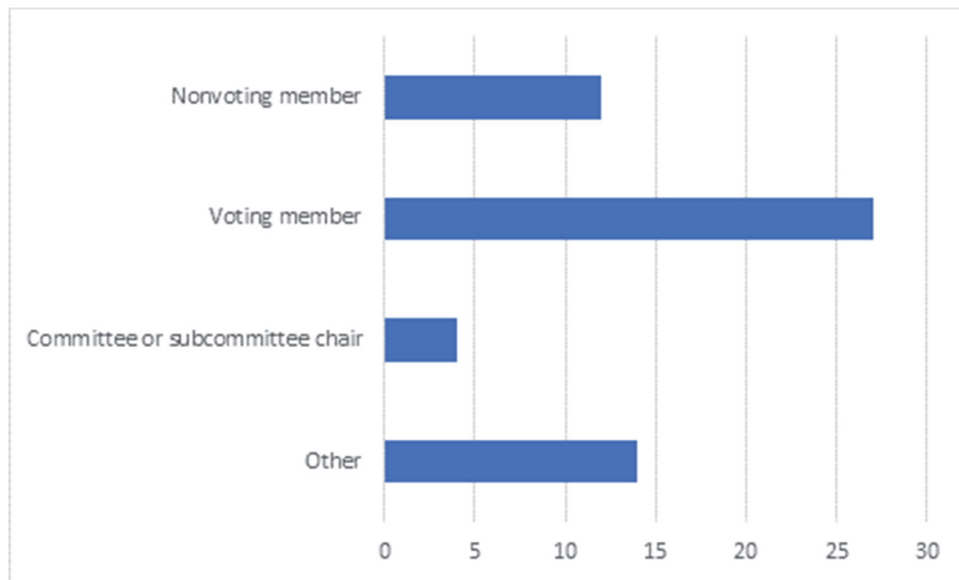
SOURCE: RAND survey of researchers in NIST Fire Research Division, September 2019.

NOTE: Fourteen researchers reported involvement in more than one SDO over the course of their career at NIST. Five of the 29 responding researchers reported no involvement in SDOs, and we were informed that those who did not respond to the survey were less likely to be involved in SDOs.

Researchers' involvement with these SDOs varies, as shown in Figure 2.2; they can serve as voting members or nonvoting members at different times for the same SDO. Current NIST researchers have held 27 voting member positions in various SDOs, and in four cases have served as a committee or subcommittee chair. Within some organizations, such as NFPA, certain committee or subcommittee chairs serve in a nonvoting capacity.

⁹ The sample included 27 full-time staff, three part-time staff, three contract researchers, six foreign guest researchers, and three postdoctoral associates.

Figure 2.2. Standards Development Organizations' Roles Held by Researchers in the National Institute of Standards and Technology's Fire Research Division



SOURCE: RAND survey of researchers in NIST Fire Research Division, September 2019.

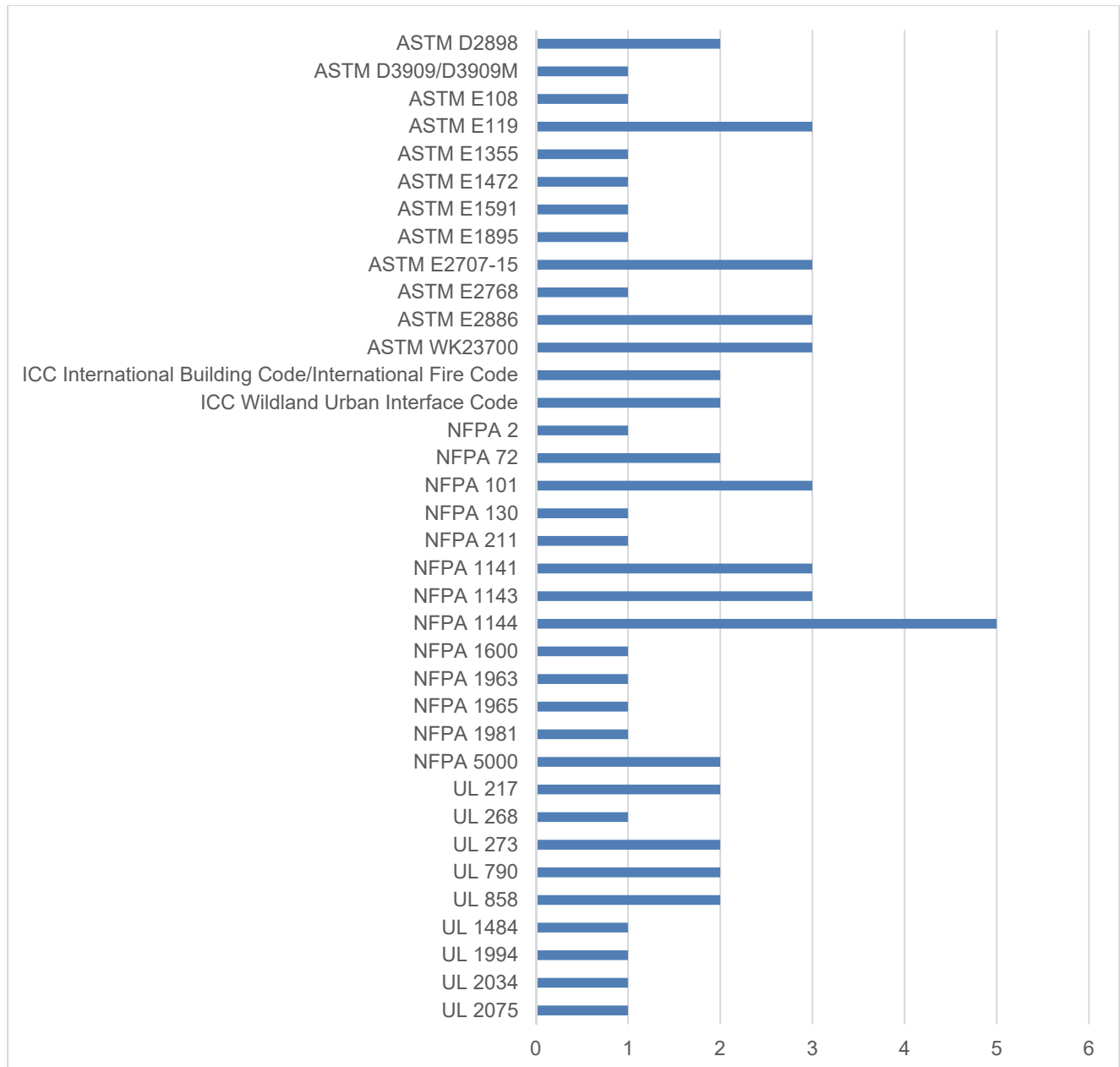
RAND spoke with representatives from NFPA, ASTM, Underwriters Laboratories, and ICC about their standards development procedures and NIST's involvement, obtained and reviewed process documentation (agendas, proposals, comments, drafts, minutes) from each of these SDOs, and attended an NFPA committee meeting. Most SDOs categorize their committee members into different groups to ensure that the groups are broadly representative. The categorizations vary across SDOs. NIST is an "R/T—Applied Research/Testing Laboratory" member on NFPA committees, a "General Interest" member at ASTM, and a "Government" member at Underwriters Laboratories.

NIST's role in conducting research that contributes to the development of fire safety standards is not unique, but it is typically one of very few research organizations represented on relevant SDO committees addressing fire safety. As a result, NIST often effectively represents the fire safety research community in SDO committee deliberations, synthesizing and presenting the current state of knowledge about the technical aspects of the standards being considered. Other U.S. fire research organizations that were identified during our research include independent research organizations such as Southwest Research Institute and the Insurance Institute for Business & Home Safety (IBHS), and the Consumer Products Safety Commission, as well as academic groups such as the University of Texas Fire Research Group.

NIST researchers indicated they participated in the development of numerous fire safety standards. Figure 2.3 shows specific standards in which researchers indicated they were involved and the number of respondents indicating their involvement in each standard. Titles for each

standard in the figure are listed in the survey instrument in Appendix A. Although this report focuses on a few specific aspects of fire safety—smoke alarms and WUI standards—Figure 2.3 demonstrates the breadth of NIST’s role in fire safety standards.

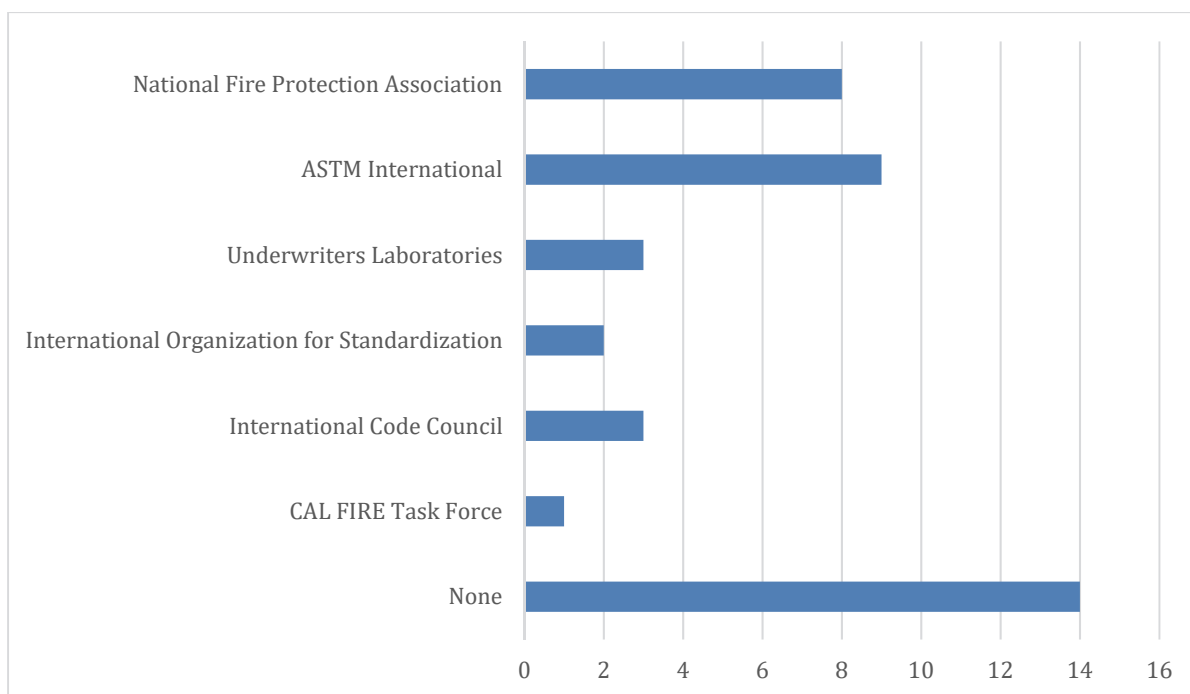
Figure 2.3. Number of National Institute of Standards and Technology Researchers Involved in Specific Fire Safety Standards



SOURCE: RAND survey of researchers in NIST Fire Research Division, September 2019.

Interviews, SDO documentation, and our survey results show that researchers in NIST’s Fire Research Division commonly provide comments during the standards development process, present research findings at SDO events, and communicate with SDO committee members about standards. Figure 2.4 shows responses from our survey of the number of NIST Fire Division researchers who have submitted formal proposals, revisions, or comments to different SDOs. In addition to these forms of engagement, many researchers reported presenting research at SDO events or participating in meetings to discuss specific standards or revisions. NIST’s Fire Research Division has twice organized workshops that take place in conjunction with ASTM committee meetings.

Figure 2.4. Have You Ever Submitted a Formal Proposal, Revision, or Comments for This Standards Development Organization?

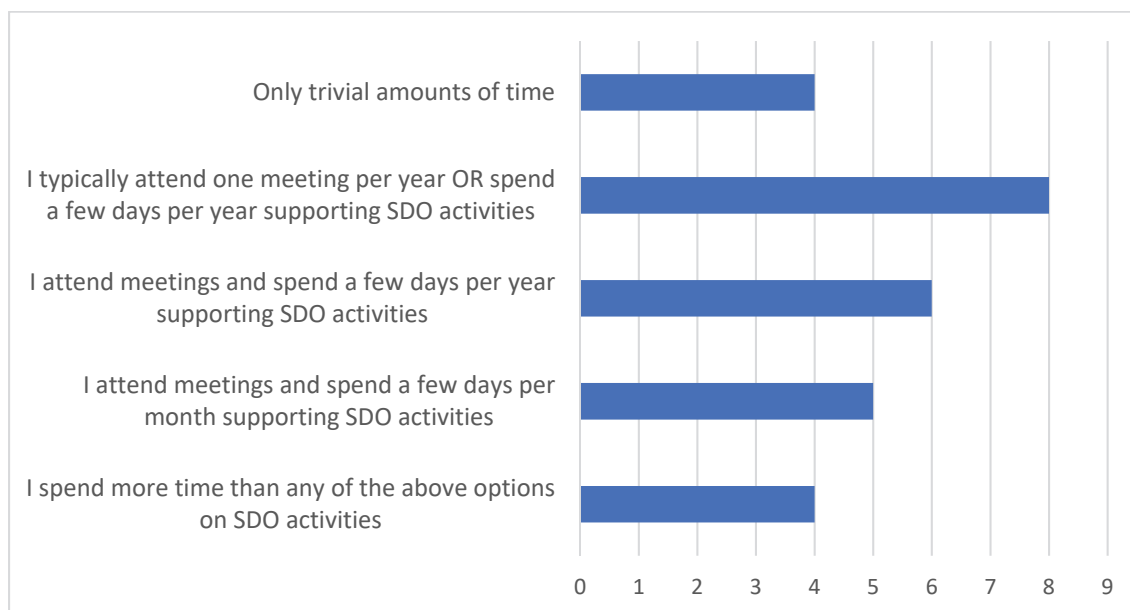


SOURCE: RAND survey of researchers in NIST Fire Research Division, September 2019.

NOTE: Five researchers reported submitting formal proposals, revisions, or comments to more than one SDO.

NIST’s role in the standards development process is a result of active engagement efforts by NIST researchers. According to our survey of NIST Fire Research Division researchers, the amount of time researchers report investing in supporting standards development can vary significantly, as illustrated in Figure 2.5. Most researchers report spending at least a few days per year attending an SDO meeting or otherwise supporting SDO activities. Many researchers report spending larger amounts of time supporting SDOs. Nine out of 29 respondents reported spending a few days per month or more supporting SDO activities, in addition to attending SDO meetings. These engagements are not new efforts, as Figure 2.6 indicates. The Fire Research

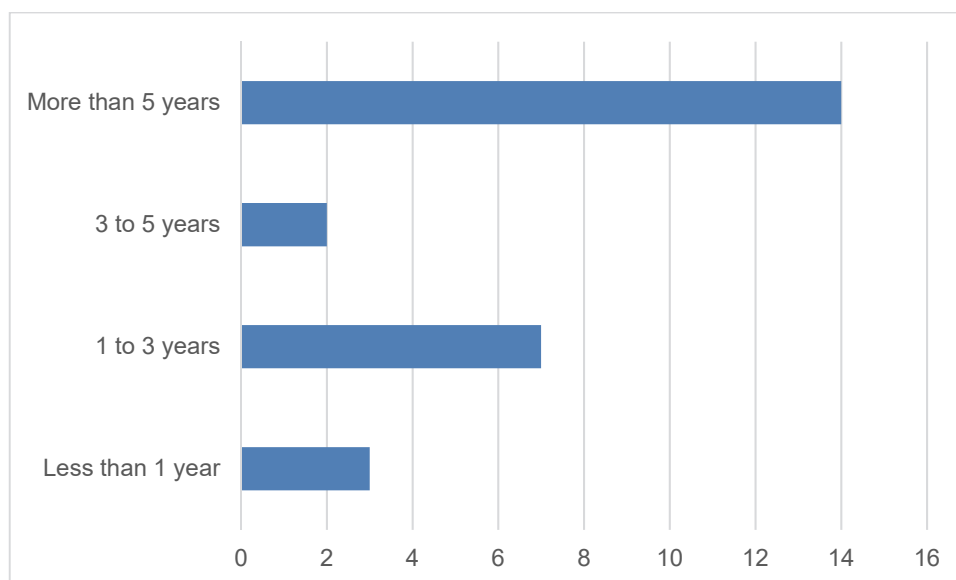
Figure 2.5. Which Most Closely Describes the Amount of Time You Spend on Activities with or for Standards Development Organizations?



SOURCE: RAND survey of researchers in NIST Fire Research Division, September 2019.

NOTE: Two of the 29 respondents did not answer this question; both of those respondents reported having no involvement with SDO activities.

Figure 2.6. What Is Your Total Length of Service for All of the Activities Listed in Figure 2.5?



SOURCE: RAND survey of researchers in NIST Fire Research Division, September 2019.

NOTE: Three of the 29 respondents did not answer this question; all three reported having no involvement with SDO activities.

Division includes over a dozen current staff who have been engaging with SDOs for more than five years, and emeritus staff also have a lengthy record of engagement with SDOs. This level of engagement reflects a long-standing strategic decision by the Fire Research Division to improve nationwide fire safety through collaboration with SDOs.

The development of standards and codes is a complex process that involves a number of different stakeholder groups that sometimes have competing interests. Arriving at a standard that all stakeholders can agree on requires extensive coordination, deliberation, and compromise. In interviews with SDO representatives and others, we sought to elicit NIST's role and performance in SDO committees beyond the participation statistics from our survey. These representatives generously shared available documentation of SDO committee activities and meetings. Some of this documentation directly cited NIST research and arguments, but the nature of the decisionmaking process makes it difficult to isolate the influence of any single individual or organization. Nonetheless, our interviews confirmed the value of NIST's contributions to the standards development process. When asked about NIST's contributions, representatives responded with statements such as "NIST engagement is *very* needed. We want more"; "NIST work has really been critical to improve the standard"; "NIST does really good work in a challenging environment"; "NIST is very thoughtful about focusing and prioritizing its research efforts to achieve the most benefit for standards development"; "NIST is very professional. The staff have great opinions and perspectives. Their contributions are invaluable. No other organization has contributed to the level of NIST." In addition, at one SDO committee meeting we attended, discussion of a particular issue was set aside until the NIST representative could return and elaborate on what the research had shown on that topic. Such comments and actions make it clear that NIST plays a central role in the development of standards and codes.

Conclusion

The development of fire safety standards is an involved process that includes basic research, development of standardized testing methods, and the coordination and integration of stakeholder needs by SDOs. As summarized generally in this chapter and more specifically in subsequent chapters, NIST has played a critical role in research, test development, and the inter-stakeholder collaboration through SDO committee work that is required to incorporate that research into standards. While NIST collaborates with a wide variety of other entities, NIST's focus on the fundamental measurement research required to support standards makes it a relatively unique organization, with other research organizations often benefiting from that work.

3. Smoke Alarm Standards

As introduced in Chapter 1, two of the case studies we used to examine the impacts of fire safety standards focus on standards associated with smoke alarms—a historical NIST research program (encouraging the adoption of smoke alarms) and an established ongoing NIST research program (improving smoke alarm performance). Figure 3.1 presents a tailored version of the logic model introduced in Chapter 1 to chart the path from NIST activities to fire outcomes associated with smoke alarm safety standards. The highlighted cells reflect the focus of this chapter. This chapter discusses NIST activities related to the development of smoke alarm safety standards and the changes to standards that were driven in part by those NIST activities. Chapter 4 discusses later steps of this smoke alarm logic model.

Figure 3.1. Logic Model of National Institute of Standards and Technology Activities and Smoke Alarm Safety Standards



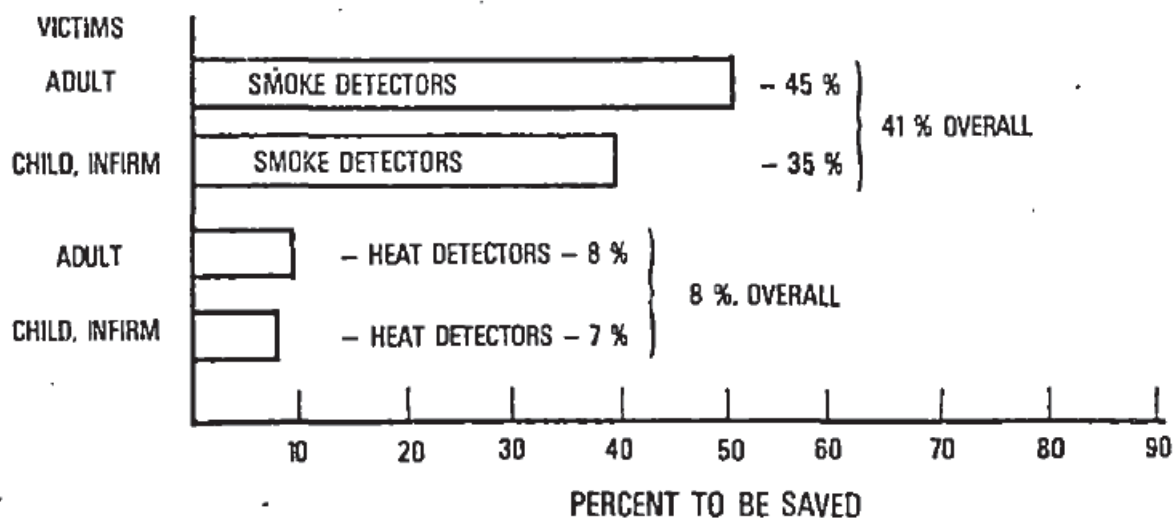
Case Study 1: The National Institute of Standards and Technology’s Role in Encouraging the Adoption of Smoke Alarms

Although smoke alarms are ubiquitous today, they were quite rare prior to the 1970s. NIST research played a critical role from the late 1960s through the late 1970s in rapidly shifting home smoke alarms from novelty to standard practice.

Research and Activities That Supported Development of Standards and Codes

NIST has long been engaged in research relevant to smoke alarm performance and use, with the earliest work on the performance of smoke detectors taking place in the 1920s and 1930s (Bukowski, 2001; Wright, 2003). However, Bright (1974) credits early theoretical work by McGuire and Ruscoe (1962) for spurring NIST’s interest in smoke alarms. McGuire and Ruscoe (1962) pointed out the theoretical life-saving value of smoke alarms (relative to heat detectors) at a time when neither was prevalent, as highlighted in Figure 3.2. Using a sample of 342 fire deaths that occurred in Ontario, Canada between 1956 and 1960, McGuire and Ruscoe used their own judgement and knowledge of each warning system’s capabilities to determine whether

**Figure 3.2. Early Research on the Theoretical Value of a Smoke Detector
Relative to a Heat Detector**



SOURCE: McGuire and Ruscoe (1962), as presented in Bright (1974).

either warning system might have prevented each death. Their conclusion was that smoke detectors would have prevented 41 percent of those deaths, while heat detectors would have prevented 8 percent. This work, along with subsequent studies, led NIST and others to focus on documenting the potential life-saving capabilities of smoke detectors.

Starting in the late 1960s, NIST's involvement in a number of projects and other activities directly contributed to a broader understanding of the benefit of home smoke alarms, their widespread adoption, and development of the first smoke alarm device standard. Table 3.1 summarizes several important studies and milestones, which are discussed below.

An important early contribution by NIST occurred during the U.S. Department of Housing and Urban Development's (HUD) Operation Breakthrough program, which ran from 1969 through the early 1970s. The purpose of this demonstration program was to incentivize the development and adoption of new home building technologies and codes. NIST was charged with developing model building code "Guide Criteria." NIST researchers included the installation of smoke alarms as part of the Guide Criteria. Although smoke alarms were not actually installed in the ~ 2,800 demonstration homes built as part of Operation Breakthrough, this was the first recommendation for their use in homes and is widely credited for introducing smoke alarms into building codes (Staats, 1976; Foote, 1995; Bukowski, 2001).

When Hurricane Agnes struck in 1972, HUD provided 17,000 mobile homes for residents in Pennsylvania displaced by flooding. In choosing the specifications, HUD asked NIST to apply some of the lessons learned from Operation Breakthrough. Since fire losses in mobile homes were known to be much higher than in conventional homes, NIST successfully recommended

Table 3.1. Timeline of the National Institute of Standards and Technology’s Key Contribution to Smoke Alarm Adoption and Standardization

Date	Event	NIST Role	Impact
Late 1960s	Operation Breakthrough initiative to develop new building technologies	NIST was charged with developing building code Guide Criteria for demonstration projects	• NIST Guide Criteria included installing smoke alarms in all homes
1972	Hurricane Agnes	Based on NIST Guide Criteria from Operation Breakthrough, smoke alarms were installed in 17,000 mobile homes provided for temporary housing	• Smoke alarms greatly reduced fire deaths and injuries relative to homes without alarms • Mobile home industry subsequently voluntarily required smoke alarms in all units
1973	Collaborative research with UL to develop a smoke alarm standard	Technical research on smoke alarm performance	• Introduction of UL 217 • Smoke alarm production increased from 50,000 nationwide in 1971 to 12–14 million in 1977
1975, 1977	Indiana Dunes Tests	Full-scale tests of commercial smoke alarms in actual homes	• Revealed superior performance of smoke alarms over heat detectors • NFPA 74 and ordinances began requiring smoke alarms on every floor of new and existing homes • Fire deaths in compliant homes began dropping precipitously • U.S. fire deaths by dropped by 50% between 1975 and 1998

that smoke alarms be installed in the mobile homes. Fire data from these mobile homes over the next few years showed remarkable benefits from the smoke alarms’ installation: while the number of fires was no different from expected fire rates for mobile homes without smoke alarms, the number of deaths and injuries from these fires was far lower than expected rates, indicating that smoke alarms provide valuable warning time that allows occupants to safely escape. These results led the mobile home manufacturing industry to begin including smoke alarms in all mobile homes, which represented the first systematic policy of installing smoke alarms in homes (Gross, 1991; Bukowski, 2001; Wright, 2003).

In addition to efforts promoting the inclusion of smoke alarms in homes, NIST also sought to advance the effectiveness of smoke alarm technology. Curious about the results from the deployment of alarms after Hurricane Agnes, NIST and UL collaborated on an effort to test the performance of commercially available smoke alarms. This work identified a number of design improvements and specifications related to sensitivity, electrical requirements, and testing and led to the first smoke alarm device standard, UL 217: Standard for Smoke Alarms. The first edition of this standard was introduced in 1974 (Bukowski, 2001). The introduction of this standard and the growing adoption of ordinances requiring smoke alarms led smoke alarm production to increase from 50,000 units nationwide in 1971 to 12–14 million units in 1977 (Gross, 1991).

Some of the most influential NIST research was informally known as the Indiana Dunes Tests (Bukowski et al., 1975; Harpe, Waterman, and Christian, 1977). Prior to this work, information about smoke alarm performance had been based on laboratory data and engineering judgement. The Indiana Dunes Tests, conducted in abandoned single-family homes located at the Indiana Dunes National Lakeshore, were the first full-scale tests of smoke alarm performance under conditions simulating actual home fires. They measured the performance of commercial smoke alarms in fires of real furniture in actual homes under controlled conditions.

These tests provided a number of important observations and findings that led to improved understanding of fire development, smoke generation and movement, and smoke alarm performance. Some of the most important contributions included the following:

- the introduction of the practice of reporting smoke alarm performance in terms of the available escape time (the time interval between when the alarm sounds and when conditions become untenable for safe escape) compared with the required escape time (the time required to exit the home)
- the discovery of the superior performance of smoke alarms compared with heat detectors; heat detectors consistently failed to provide adequate escape time, while smoke alarms routinely provided adequate time. This further bolstered the case for the benefits of smoke alarms.
- the observation that smoke alarms on the second floor of a home had marginal performance for fires on the first floor. At the time of the tests, the standard on smoke alarm placement required smoke alarms only on floors with bedrooms. Thus, homes in which all bedrooms were upstairs were not required to have a smoke alarm on the ground floor.
- the finding that fires originating within closed bedrooms led to lethal conditions in the bedroom before a smoke alarm outside the bedroom was triggered
- the observation that photoelectric detectors were relatively more sensitive to smoldering fires and that ionization detectors were relatively more sensitive to flaming fires
- the finding that heating and air conditioning systems, stairwells, and other home layout features influence the movement of smoke and performance of smoke alarms.

Changes to Standards

These tests had an important impact on the use of smoke alarms. NFPA 74: Recommended Good Practices for the Installation of Automatic Fire Alarm Systems for Private Dwellings was revised to require smoke alarms on every floor of homes;¹⁰ the growth of local ordinances requiring smoke alarms accelerated, in some cases making smoke alarm requirements apply to existing homes; and, most importantly, fire deaths, which had been steady for many years, began to drop significantly in compliant homes. Table 3.2 presents a timeline of key smoke alarm

¹⁰ This standard, later renamed “Standard for the Installation, Maintenance, and Use of Household Fire Warning Equipment,” was incorporated into NFPA 72: National Fire Alarm and Signaling Code in 1993 and subsequently withdrawn.

Table 3.2. Timeline of Key Residential Smoke Alarm Standards

Date	Development
1967	First edition of NFPA 74, Standard on the Installation, Maintenance, and Use of Household Fire Warning Equipment
~ 1970	NFPA 74 first includes requirements on smoke alarm locations
1974	First edition of UL 217, Standard for Smoke Alarms

standards and code developments during the 1960s and 1970s. A decline in U.S. fire deaths by 50 percent between 1975 and 1998 has been largely attributed to the widespread adoption of smoke alarms (Bukowski, 2001).

Participation in Standards Development Organizations

NIST researchers have been involved in the development of home smoke alarm standards and codes at least since the mid-1960s. Information about NIST's involvement in SDOs during this time period is limited, but NIST's influence is clear. Research by Richard Bright, of NIST, was central to the inclusion of smoke alarms in the Operation Breakthrough building code Guide Criteria and in the mobile homes after Hurricane Agnes. It was also a contributing factor in early tests of commercial smoke alarms, which revealed the need for a device standard. Although technically at UL at the time, Richard Bukowski worked with NIST (and in residence at NIST for part of the time) on smoke alarm research that led to the development of UL 217 and was the leader of the Indiana Dunes Tests. He moved to NIST full time shortly thereafter. He was an active member of the UL 217/268 Standard Technical Panel and NFPA 72 Technical Committees until his retirement in the mid-2000s.

Case Study 2: The National Institute of Standards and Technology's Role in Updated Smoke Alarm Performance Requirements

Since the mid-1970s, the use of smoke alarms in homes has grown substantially, largely facilitated by the adoption of state and local ordinances requiring their use. While the early smoke alarm research described in the previous section focused on the development of a standard for smoke alarms in homes and on their adoption, this second phase of smoke alarm work targeted specific aspects of smoke alarm performance: updated fire tests on synthetic furnishing materials and resistance to nuisance alarms.

Research and Activities That Support Development of Standards and Codes

For one aspect of this work, NIST researchers focused on revisiting smoke alarm design and testing in light of the shift to the use of largely synthetic materials in upholstered furniture. These materials (polyurethane and plastics) were known to burn more quickly and have different smoke generation characteristics than do natural materials. While the public's transition to synthetic

furnishing materials had been occurring for many years, smoke alarms were still being designed and tested to respond to fires from natural furnishing materials.

Another aspect of this research focused on reducing nuisance alarms, stemming primarily from cooking aerosols and bathroom shower mist. Beyond being inconvenient, nuisance alarms lead home occupants to disable smoke alarms, thereby leaving them unprotected. NFPA studies have found that 17 percent of civilian fire deaths occurred in homes with nonoperational smoke alarms and that nuisance alarms were the leading cause for disabling smoke alarms (Ahrens, 2004; 2019). A survey conducted by RAND as part of this study and discussed further in Chapter 3 found that more than one-third of households reported having disabled a smoke alarm to prevent nuisance alarms, providing compelling evidence that this issue is widespread. Causes and consequences of nuisance alarms are discussed in more detail in NFPA Task Group on Smoke Detection Follow-Up (2009).

Table 3.3 lists some of the key developments in this second phase of NIST smoke alarm research.

Table 3.3. Timeline of the National Institute of Standards and Technology’s Key Contributions to Updated Smoke Alarm Performance Requirements

Date	Event	NIST Role	Impact
2000–2004; 2008	Home Smoke Alarm Tests	Research experiments on smoke alarm performance were conducted from 2000 to 2002; NIST published the original report in 2004, and a revised version in 2008	Measurement of smoke production rates for synthetic furnishing materials; characterization of nuisance alarm potential for different cooking scenarios
2008	NFPA 72 Task Group on Smoke Detection Technology	Staff members in the task group (TG) and on NFPA 72 Technical Committee; NIST research informed TG recommendations	Developed recommendations for minimum distances for locating smoke alarms away from cooking appliances; recommendations adopted in 2010 edition of NFPA 72
2008–2015	UL 217/268 Task Group on Reducing Nuisance Alarms and New Fire Test Task Group	Technical research & publications, staff member in TGs and on UL 217/268 Technical Panel, and multiple research presentations to SDOs and elsewhere	2013 edition of NFPA 72 added requirement that by 2016 smoke alarms located near cooking appliances must be resistant to nuisance alarms and that by 2019 all smoke alarms must be resistant to nuisance alarms, although these deadlines were subsequently delayed. Edition 7 of UL 217 (2015) included new cooking nuisance alarm resistance test and polyurethane fire tests that took effect May 2020
2014	NIST Technical Note 1837 (Cleary, 2014)	Technical research providing performance criteria for new smoldering and flaming polyurethane foam fire tests proposed for ANSI/UL 217 and ANSI/UL 268	Provided an agreed-upon set of test designs and test performance requirements that were incorporated into a 7th edition of UL 217 (2015), resolving a previous impasse on efforts to reduce nuisance alarms

The first major effort to reevaluate smoke alarm design and performance was the Home Smoke Alarm Tests conducted from 2000–2002 (Bukowski et al., 2008). These tests, which were conducted in cooperation with several other organizations, were in some ways similar to the Indiana Dunes tests in that they examined the performance of commercial detectors in realistic home settings. However, they differed in several ways from the Indiana Dunes tests, including using furnishings constructed with modern materials and exploring the occurrence of nuisance alarms.

A key contribution of this work was measurement of smoke development rates for fires of synthetic furnishing materials, which were significantly faster than for the natural materials used in the Indiana Dunes Tests. The impact of more rapid fire escalation was exacerbated by researchers imposing more stringent criteria for the onset of unsafe conditions. These effects combined to reduce the available escape time, thus decreasing the effective performance level of smoke alarms. The tests also confirmed the greater relative sensitivities of photoelectric and ionization detectors to smoldering and flaming fires, respectively. Performance of commercially available smoke alarms of either type was nonetheless generally sufficient to provide adequate escape time.

A second major contribution of these tests was the first systematic investigation of the conditions that generate nuisance alarms. Tests were conducted for several different types of typical cooking procedures and other activities (e.g., toasting, frying, broiling, burning candles, bathroom showering). The results showed that smoke alarms should not be located near cooking appliances or bathrooms. The tests also showed that ionization detectors were more sensitive than photoelectric detectors to nuisance alarms stemming from cooking activities. Although the problem of nuisance alarms had long been recognized and had begun to be addressed through restrictions on smoke alarm placement as early as 1993, this was the first time the nuisance alarm problem had been tackled in a controlled way.

Subsequent to the Home Smoke Alarm Tests project, the NFPA 72 Technical Committee formed the Task Group on Smoke Detection Technology. Two of the TG members were NIST staff, and the Home Smoke Alarm Tests and other NIST research factored heavily in informing the TG's recommendations. The main contribution of this TG was specific recommendations about the minimum distance that smoke alarms should be located away from cooking appliances. It also explored the effectiveness of “hush” buttons, which allow users to temporarily silence the alarm signal in the case of a nuisance alarm, but found no evidence of their impact.¹¹ These recommendations were then adopted in the 2010 edition of NFPA 72, for which two NIST staff members were on the technical committee (NFPA Task Group on Smoke Detection Technology, 2008; NFPA Task Group on Smoke Detection Follow-Up, 2009).

¹¹ The intention of including a hush button is to dissuade occupants from permanently disabling smoke alarms in response to nuisance alarms.

In the ensuing years, NIST was closely involved in efforts to design and implement tests to be included in UL 217 for (a) resistance to nuisance alarms and (b) sensitivity to flaming and smoldering fires of furniture made from synthetic materials. NIST researchers conducted new experiments and presented the findings on multiple occasions (Cleary and Chernovsky, 2013; Cleary, 2014). The first outcome of these efforts was that a requirement for nuisance alarm resistance was added to NFPA 72 in the 2013 edition. This requirement was originally slated to become effective in 2016, but the effective date was subsequently extended to 2022.

Two UL task forces were created during this period to address these topics, and NIST staff and research were central to their work. The process was marked by disagreement among the UL 217 Standard Technical Panel members, and multiple proposals failed. NIST research, particularly by Cleary (2014), played a pivotal role in reaching consensus.¹² Meetings of the Standard Technical Panel meetings referred frequently to NIST research, comments by a NIST researcher, and responses to those. Ultimately a set of test designs and test performance requirements were agreed upon and incorporated into the seventh edition of UL 217, published in 2015. These new requirements became effective in May, 2020. When the new test performance requirements were established, NIST conducted a set of experiments with dozens of smoke alarm models from seven manufacturers to assess their compliance with the new standard. None of them met the new test performance requirements (Cleary, 2016).

Changes to Standards

The evolution of standard and code requirements since 1989 is shown in Table 3.4. The gradual evolution of smoke alarm placement and technology restrictions represents an increasing understanding of the conditions under which nuisance alarms occur. The revision of UL 217 in 2015 represented a fundamentally new approach to dealing with nuisance alarms: Rather than regulate the location and technology of smoke alarms, this new standard sets nuisance-resistance performance requirements that are independent of location and technology.

Experience gained from widespread smoke alarm use showed that a high proportion of smoke alarms in homes were nonoperational and that the most common reason for this was that smoke alarms had been deliberately disabled by occupants in response to repeated nuisance alarms. As the magnitude of this issue became apparent, NFPA 72, which primarily governs placement of smoke alarms, gradually introduced measures to reduce the likelihood of nuisance alarms. These measures included limiting how close smoke alarms can be placed to cooking appliances and bathrooms, requiring hush buttons, and prescribing the allowable type of detector technology.

¹² Personal communication with NIST Fire Research Division staff. We can confirm the culture of deference to and reliance on NIST's scientific expertise at SDO meetings: At a 2019 NFPA meeting attended by RAND, one point of disagreement was put on hold until the relevant NIST researcher was available to describe the associated scientific literature.

Table 3.4. Timeline of Key Residential Smoke Alarm Standard and Code Developments

Date	Development
1989 ^a	NFPA 74 Smoke alarms required outside each sleeping area and on every floor, including basements
1993	First edition of NFPA 72; NFPA 74 withdrawn - Smoke alarms required in bedrooms (new construction only) - Smoke alarms not allowed within 3 feet of a door to a kitchen or bathroom containing a shower or tub - Smoke alarms not allowed within 3 feet of supply registers of a forced air heating or cooling system
1999	NFPA 72 If within 20 feet of a cooking appliance, smoke alarm must have an alarm silencer or be photoelectric
2007	NFPA 72 Requirement for smoke alarms in bedrooms extended to include both new and existing construction
2010	NFPA 72 - Smoke alarms not allowed within 10 feet of a cooking appliance unless designed for use in close proximity to a cooking appliance, except: - Photoelectric smoke alarms may be located 6 feet or more from a cooking appliance if (a) kitchen has no partitions or headers and (b) placing it more than 10 feet away would prohibit compliance with other parts of the code - Added additional provisions for smoke alarm placement on ceilings with joists or beams
2013	NFPA 72 - If between 6 and 20 feet of a cooking appliance, smoke alarms must be resistant to nuisance alarms (effective in 2016) - All smoke alarms must be resistant to nuisance alarms (effective in 2019)
2015	UL 217 - Added new smoke alarm tests and test performance requirements, effective in 2020 - Smoldering and flaming polyurethane fire tests - Broiling hamburger nuisance alarm test
2016	NFPA 72 If between 6 and 20 feet of a cooking appliance, smoke alarms must be resistant to nuisance alarms (effective in 2019)
2019	NFPA 72 - If between 6 and 20 feet of a cooking appliance, smoke alarms must be resistant to nuisance alarms (effective in 2022) - Removed requirement that all smoke alarms must be resistant to nuisance alarms

NOTE: ^a Status as of this date, but possibly first introduced earlier.

Recognizing that these were second-best measures, the standards development community, led by NIST research and guided by NIST staff involvement in task force and committee activities, sought to develop a requirement for resistance to nuisance alarms that does not depend on smoke alarm location or technology. With the implementation of this new requirement beginning in 2020, future editions of NFPA 72 may no longer need to include smoke alarm placement and technology restrictions intended to minimize nuisance alarms. Indeed, a proposal for the 2022 edition of NFPA 72 removes all existing occurrences of prescribing a particular smoke alarm detection technology.

The other major outcome of this phase of smoke alarm research, updating test performance requirements to reflect conditions created in fires of modern synthetic furnishing materials, is the sort of revision expected to be necessary from time to time as the environment in which a technology is used evolves.

Participation in Standards Development Organizations

NIST has had a constant presence on the key smoke alarm SDO committees since the 1970s. NIST researcher Richard Bukowski was an active member of the UL 217/268 Standard Technical Panel and of NFPA 72 Technical Committees throughout his career, starting in the 1970s until his retirement in the late 2000s. Thomas Cleary of NIST phased into both of these roles in the mid-2000s and remains in them currently. NIST smoke alarm-related membership in SDOs is summarized in Table 3.5.

Table 3.5. The National Institute of Standards and Technology’s Involvement in Smoke Alarm Standards Development Organization Committees

SDO	Standard	Committee	Role	Category	Time Period
NFPA	NFPA 72: National Fire Alarm and Signaling Code	Single- and Multiple-Station Alarms and Household Fire Alarm Systems	Voting member, chair (1993–1999)	R/T—Applied Research/Testing	1987–present
NFPA	NFPA 72: National Fire Alarm and Signaling Code	Technical correlating committee	Voting member, nonvoting member (1996–1999)	R/T—Applied Research/Testing	1993–2010
UL	UL 217: Standard for Smoke Alarms	Smoke detectors and alarms	Member	Government	1974–present
ICC	International Building Code, International Fire Code	International Building Code Fire Safety Code Committee	Member		Unknown–present ^a

NOTE: ^aJason Averill was on ICC’s committee until approximately 2012. As of 2020, Nelson Bryner is on several ICC committees involving fire codes, although not on the smoke alarm committee. (Personal communication with NIST Fire Research Division staff.)

Review of UL standard technical panel and NFPA technical committee materials shows that NIST has maintained a central role in standard and code development through research, participation in committees and task groups, presentations to committees and task groups, development of proposals for standard revisions, comments on other proposals, and committee votes.¹³

UL 217 standard development materials show that NIST comments and proposals, as well as references to NIST research reports, proposals, comments, are ubiquitous throughout the highly technical, often contentious exchanges. NIST is one of the primary sources of research, along with research from UL, the Consumer Products Safety Commission, and NFPA’s Fire Protection Research Foundation.

¹³ Documentation of the UL 217 standard development process spanning 2007–2015 was provided by UL. Documentation of the NFPA 72 standard development process spanning 1987–2019 is available at NFPA (2019a).

NFPA 72 standard development materials similarly refer to NIST research, proposals, comments, and votes. A new edition of NFPA 72 is released every three years. Proposals and comments from NIST researchers are present in several of the revisions, and references to NIST work are made in proposals and comments from other SDO members in every round of revisions. In addition, multiple NIST research reports have been cited in NFPA 72 since 1990.

Conclusion

NIST research and other activity summarized in Tables 3.1, 3.3, and 3.5 provided important contributions to our understanding of the effectiveness of smoke alarms, the development of smoke alarm standards, and the widespread adoption of smoke alarms. This work also supported subsequent improvements in smoke alarm performance and reducing the prevalence of nuisance alarms. NIST involvement in early smoke alarm research started in the late 1960s, and much critical work demonstrating the effectiveness and potential benefits of smoke alarms occurred in the 1970s. This work was a critical element in transformation of smoke alarms from a novelty to a conventional household feature.

With the efficacy of smoke alarms solidly proven by the early 2000s, subsequent NIST work has focused on minimizing nuisance alarms. As will be discussed in Chapter 4, this work is important for public safety, as households commonly disable smoke alarms to prevent nuisance alarms.

4. The Impact of Smoke Alarm Standards on Fire Outcomes

As discussed in Chapter 3, NIST research and participation in formal standards development processes have contributed substantially to the development of smoke alarm standards. These standards cover requirements for the number and location of smoke alarms in homes, smoke alarm performance, and smoke alarm test methods. In this chapter, we focus on quantitative analysis of the relationship between changes to building codes (the third step of the logic model) and improved fire outcomes (the fifth step of the logic model) in which these standards are adopted in building codes and generate benefits, as shown in Figure 4.1. We are not aware of systematic nation-wide records that would allow us to observe and track the intermediary step of changes to building designs and retrofits of existing buildings.

Figure 4.1. Logic Model of National Institute of Standards and Technology Activities and Smoke Alarm Safety Standards



To evaluate the value of smoke alarm safety standards, we examined the relationship between a state's adoption of specific editions of smoke alarm standards into the residential building code and fire outcomes in that state. If more current editions of smoke alarm standards are more protective than older editions, then states with codes that incorporate more current standards are expected to have more favorable fire outcomes (reduced fire losses), assuming other conditions are the same. The link between the adoption of smoke alarm standards and fire outcomes occurs through the incorporation of standards into building codes, application and enforcement of those codes in the residential building stock,¹⁴ and the effectiveness of those standards in improving fire outcomes. If codes are not applied, enforced, and effective, their adoption is of no consequence.

¹⁴ Most building codes apply to new construction only, so they work their way into the building stock through addition or replacement of buildings.

Previous Research on the Benefit of Code Adoption, Enforcement, and Smoke Alarms

Past studies have examined the link between steps four and five of the logic model in controlled experiments concerning the effectiveness of installed smoke alarms in improving fire outcomes. We are not aware of any prior studies that examine the relationship between code adoption and fire safety outcomes, although such studies have been done for other hazards.

The Benefits of Code Adoption and Enforcement in Other Settings

Research institutes that support the insurance industry have focused much attention on building code enforcement, with particular attention to rating states' enforcement quality so that insurers can incorporate that information into the insurance rates and risk assessments. IBHS provides state-level ratings that are intended to serve as an aggregated reflection of code adoption, enforcement, training, and implementation for 18 hurricane-prone states (IBHS, 2018). A similar ranking provided by ISO is intended to reflect both the strength and the enforcement of codes, as well as a ranking of communities' fire suppression capabilities.¹⁵ Metrics such as these are used by insurers to help determine risk.

IBHS (2014) shows buildings constructed after the adoptions of 1996 building codes suffered less damage in Hurricane Charlie than those built prior to the 1996 codes.¹⁶ Similarly, IBHS (2009) shows that homes built to the codes outlined in the Fortified program, a voluntary construction and reroofing program based on building codes developed by IBHS, suffered less damage in Hurricane Ike than other homes.¹⁷ Recent academic studies have found similar results. Several studies have examined Florida's adoption of a new statewide code in 2001 and found that that doing so reduced windstorm losses by 72 percent (Simmons, Czajkowski, and Done, 2018; Done, Simmons, and Czajkowski, 2018) and that intensive local-level implementation of these codes further reduced damages by 15–25 percent (Czajkowski, Simmons, and Done, 2017). As mentioned previously, we are not aware of any similar studies on the link between codes and fire safety outcomes.

The Benefits of Smoke Alarms

For evidence on the effectiveness of fire safety codes' requirements, a number of studies have examined the effectiveness of smoke alarms. The general approach is to compare outcomes of fires in occupied homes that have smoke alarms with those in occupied homes that do not.

¹⁵ More information about ISO's Building Code Effectiveness Grading Schedule is available at Thomure (undated). More information about ISO's measure of states' fire protection capabilities is available at ISO (undated),

¹⁶ See also IBHS (undated a).

¹⁷ See also IBHS (undated a).

This approach examines the impact of the smoke alarm technology itself and is independent of any variation in standards, codes, or code application and enforcement. While the effectiveness of smoke alarms depends on details such as the type, number, and location of smoke alarms, studies of smoke alarm effectiveness generally simply record the presence or absence of at least one working smoke alarm in the home. The most common fire outcome used in studies of smoke alarm effectiveness is fire deaths. Because all data are collected through local fire departments, such analyses present estimates for reported fires only.

We searched the academic and other technical literature for analyses of the effectiveness of smoke alarms. The studies we identified are summarized in Table 4.1. To facilitate comparison, we recast the results for each study in terms of the fatality rate (fatalities per reported fire or fatal fires per reported fire¹⁸) in homes with working smoke alarms divided by the fatality rate in homes without working smoke alarms. This ratio represents the relative risk of fatalities in homes with and without smoke alarms. A relative risk value of less than one indicates that the fatality rate in homes with smoke alarms is less than that in homes without smoke alarms.

Table 4.1. Relative Risk of Fatalities per Fire in Homes With and Without Smoke Alarms

Study	Relative Risk ^a	Date	Location	Data Source
Runyan et al. (1992)	0.428	1988–1989	North Carolina	Interviews with fire officials
Rhode et al. (2016)	0.463	1998–2013	Queensland, Australia	Fire dept. data
Ahrens (2008)	0.487	2000–2004	United States	NFIRS ^b
Ahrens (2011)	0.509	2003–2006	United States	NFIRS
Ahrens (2019)	0.463	2012–2016	United States	NFIRS
Gilbert (2018)	1.46	2009–2016	United States	NFIRS

NOTES:

^a Relative risk = (fatality rate in homes with a smoke alarm) / (fatality rate in homes without a smoke alarm), where fatality rate = $\sum \text{fatalities} / \sum \text{reported fires}$ or $\sum \text{fatal fires} / \sum \text{reported fires}$.

^b NFIRS = National Fire Incident Reporting System, which we also use for this report's subsequent analysis.

The first five studies in Table 4.1 show a remarkably consistent relative risk of 0.4 to 0.5, indicating that the presence of a smoke alarm is associated with a fatality rate of less than half of that of homes without a smoke alarm. This indicates that smoke alarms provide early warning of a fire, allowing occupants to escape injury. Gilbert (2018) shows the opposite effect—namely, that the fatality rate in homes with a smoke alarm is *greater* than that in homes without a smoke alarm. The author infers that this somewhat surprising finding results from occupants preferentially

¹⁸ As long as the number of fatalities per fatal fire is the same in cases with and without smoke alarms, both measures of fatality rate will give the same relative risk.

extinguishing (and hence not reporting) less dangerous fires when smoke alarms are present, leaving only the more dangerous fires in the data for reported fires.

The relative risks shown in Table 4.1 provide an estimate of the life-saving effectiveness of smoke alarms per fire. But we are ultimately interested in the effect of smoke alarms on fatalities per home. Hence, any association between the presence of smoke alarms and the incidence of fires is an important consideration as well.

Several of the studies in Table 4.1 show that the number of fires per home is far lower for homes with smoke alarms than for homes without smoke alarms. The mechanism for this is not entirely clear, but the best explanation is that smoke alarms allow occupants to prevent an imminent fire (Gilbert, 2018; Ahrens, 2019). Further, Gilbert (2018) also finds a difference between the reporting rate of fires in homes with and without smoke alarms. As with the fire incidence rate, the fire reporting rate is lower in homes with smoke alarms than in homes without. Homes with smoke alarms thus have fewer fires per home, fewer reported fires per actual fire, and, with the exception of one study, fewer fatalities per reported fire than homes without smoke alarms. These factors combine to result in far fewer fatalities per home in homes with smoke alarms compared with homes without smoke alarms.

Using the results of Gilbert (2018), we have estimated the relative risk of fatalities per home in homes with and without smoke alarms for each of the studies listed in Table 4.1. When considering the combined effects of the reductions in fires per home, reported fires per actual fire, and fatalities per reported fire, the risk of a fire fatality in a home with a smoke alarm is 7 to 26 times lower than in a home without a smoke alarm (Table 4.2).

Table 4.2. Relative Risk of Fatalities per Home in Homes With and Without Smoke Alarms

Study	Relative Risk, Fires per Home	Relative Risk, Reported Fires per Fire	Relative Risk, Fatalities per Reported Fire^b	Relative Risk, Fatalities per Home
Runyan et al. (1992)			0.428	0.038
Rhode et al. (2016)			0.463	0.042
Ahrens (2008)			0.487	0.044
Ahrens (2011)			0.509	0.046
Ahrens (2019)			0.463	0.042
Gilbert (2018)	0.417	0.215 ^a	1.46	0.131

NOTES:

^aAverage of values from Table 3 of Gilbert (2018).

^b From Table 4.1.

Interpretations of these results are complicated by at least three issues.

First, none of the studies attempts to match cases with and without smoke alarms. If, for example, factors other than smoke alarms that influence the risk of fire fatalities (e.g., construction,

furnishings, occupant behaviors) differ systematically between homes with and without smoke alarms, then the actual effect of smoke alarms would differ from the reported values. We are not aware of any evidence for such differences, but it seems reasonable that smoke alarms are more prevalent in newer homes, which may pose lower fire risk for other reasons as well.

Second, many fire records do not report on the presence or absence of a smoke alarm and are therefore excluded from the analyses. Evidence indicates that smoke alarm presence or absence is reported more often in fatal fires than in nonfatal fires (Gilbert, 2018). However, the effect of this inconsistency depends on whether the underreporting differs between homes with smoke alarms and homes without smoke alarms, which is unknown.

Finally, not all of the studies confirm whether a smoke alarm present at a fire was functional or not, and this introduces uncertainty in the assignment of smoke alarm presence or absence.

Having discussed the strong association between the presence of a smoke alarm and the reduction in the risk of fire fatalities, we now return to the larger question of the relationship between the adoption of smoke alarm standards into building codes and the risk of fire fatalities.

Adoption of Smoke Alarm Standards into Building Codes

Smoke alarm standards have been incorporated into national model codes, which have in turn have been widely (although not uniformly) adopted by state and municipal building departments since the 1970s. State and local governments voluntarily adopt (and revise) model codes through legislative or regulatory actions. State agencies tasked with administering statewide codes typically release a public notice of intent to consider and adopt new codes. In most cases, the public can review proposed codes and formally submit proposals to modify them. Several states allow local authorities to adopt model codes in the absence of a statewide code, a policy often referred to as “home rule.” Historically, some states, such as New York and Wisconsin, developed their own codes. Adoption procedures, including amendments, and timelines to review and/or update codes are set by individual states.

The earliest national model code in the United States was the Uniform Building Code, developed in 1927 by the International Council of Building Officials (ICBO) and used primarily in the western states. Until 1994, three organizations developed different building codes for use in different parts of the country.¹⁹ In 1994, the three organizations formed the ICC as a nonprofit

¹⁹ The Standard Building Code—originally the Southern Standard Building Code—was first published in 1945 by the Southern Building Code Congress International and used mainly in the southern states. The Building Officials Conference of America, later known as the Building Officials and Code Administrators International, published the first edition of the Basic/National Building Code in 1950, which was used in the northeast, mid-Atlantic, and midwestern states. Reflecting fundamental geographical differences, the Uniform Building Code emphasized structural provisions for proper seismic design (for a region prone to earthquakes), the Standard Building Code emphasized wind-resistant design (for a region prone to hurricanes), and the National Building Code addressed design snow loads on building roofs (for a region prone to harsher winters).

organization to develop a single set of comprehensive and uniform standards to be applied throughout the United States. The International Building Code was the first code published by the ICC in 2000.

Several of the model codes developed by ICC—in particular the International Residential Code—cite fire safety standards developed by SDOs, such as NFPA 72 and UL 217. Thus, state and local governments that adopt these model codes also adopt the relevant smoke alarm standards. As described in Chapter 3, NIST research has played a substantial role in the development of these smoke alarm standards and is directly referenced in NFPA’s National Fire Alarm and Signaling Code (NFPA 72). NFPA standards are revised and updated every three to five years; NFPA 72 was last revised in 2019.²⁰ However, states typically revise and update their building and fire codes on a three-year cycle (in some cases six years). Not all states have adopted codes referencing the most recent edition of NFPA 72, and some states have not adopted any state-wide code. Local codes may impose stricter requirements in addition to any state-wide codes, but local codes cannot grant exceptions to state-wide codes.

Figure 4.2 shows the edition of NFPA 72 reflected in statewide residential codes as a function of time. Since 2003, most states have adopted a statewide minimum building and/or residential code. Fourteen states currently have no statewide minimum building or residential code. Nine states have adopted the 2018 International Residential Code, which in turn references the 2016 edition of NFPA 72.²¹ In the next section, we take advantage of variation in the edition of NFPA 72 that states have in force to examine the relationship between the edition of a smoke alarm standard in force and the fire outcomes experienced. If a more recent edition of NFPA 72 is more protective, states with codes that incorporate more recent editions are expected to have more favorable fire outcomes.

The Impact of Smoke Alarm Standards on Fire Outcomes, 2003–2017

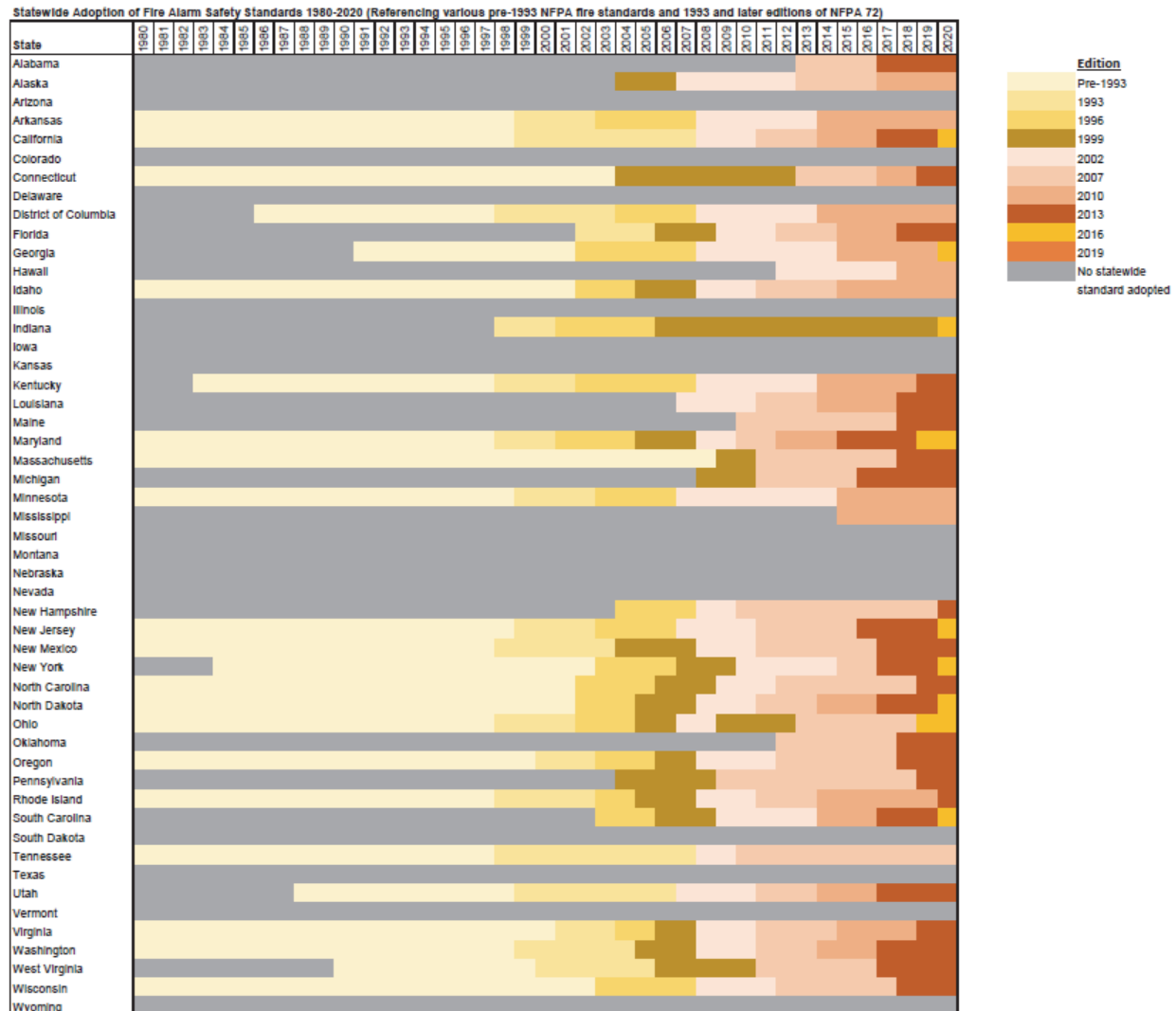
Our analysis seeks to answer the following question: Are more current smoke alarm standards in statewide minimum building and residential codes associated with improved fire outcomes? To answer this question, we examine the relationship between the smoke alarm

Efforts to develop a single national model code began well before 1994. In 1972, the Council of American Building Officials was created by the three model code organizations to provide the means to address common concerns and identify conflicts between the model codes. One of the early joint code writing efforts was a residential code, the Council of American Building Officials One and Two-Family Dwelling Code, which was adopted by reference into the three model building codes. The last Uniform Building Code was published in 1997 and the last Standard Building and National Building Codes were published in 1999.

²⁰ The first modern edition of NFPA 72, published in 1993, consolidated several earlier standards, including NFPA 71 (1989 ed.), NFPA 72 (1990 ed.), and NFPA 74 (1989 ed.).

²¹ The full name of the code is the “International Residential Code for One- and Two-Family Dwellings.” This code applies to detached one and two-family homes and townhouses, and some small owner-occupied bed and breakfast-style hotels with less than five guests. Other categories of housing would fall under the International Building Code.

Figure 4.2. Statewide Adoption of Codes Incorporating National Fire Protection Association 72 by State, Edition, and Year



SOURCE: RAND analysis of state agency records on the adoption of statewide building and residential codes for 50 states and the District of Columbia.

NOTES: The state agencies responsible for building and residential codes were identified using NFPA (undated a). The current edition of the building or residential code for each state was identified using ICC (undated c).

standards adopted in state building and/or residential codes and fire outcomes. As noted in Table 3.4, the recent changes to the smoke alarm standards that we examined included several changes related to reduction of nuisance alarms near kitchens and the inclusion of smoke alarms in bedrooms. More recent editions generally require more smoke alarms in higher-risk locations, interconnection among separate smoke alarms, more resistance to nuisance alarms, and testing and sensitivity related to modern synthetic furnishing materials, so one might expect homes that are required to meet more recent standards to have improved fire safety outcomes.

As shown in Figure 4.2, states that have adopted the same edition of NFPA 72 have done so at different points in time, while other states have never adopted those standards into their statewide building codes. Further, because building codes are rarely retroactive, the proportion of a state's housing stock built after the code was adopted serves as a reasonable proxy for the proportion of houses that were required to meet that building code.²² Consequently, we investigate whether states with a higher proportion of their housing stock built subsequent to the adoption of a specific edition of NFPA 72 have fewer severe house fires than states with little or no housing stock required to meet those standards.²³ We emphasize that our analysis does not directly compare fire safety outcomes between homes with and without smoke alarms. Rather, our analysis compares fire safety outcomes between states where more or fewer homes are likely to be subject to recent fire safety standards.

Data Sources and Statistical Methods

We rely on residential fire outcome data from NFIRS to calculate per capita fire frequency for fires of different severities. The information that fire departments report to NFIRS includes the location of the fire, the extent to which each fire spread within and between areas, and whether any injuries or fatalities occurred. We use this information, along with intercensal estimates of the number of housing units by state from the U.S. Census Bureau, to estimate number of residential fires of different severities among homes built since enactment of specific editions of NFPA 72. We also estimate the number of injuries and fatalities that occurred in relation to the proportion of homes built since specific editions of NFPA 72 were enacted.²⁴

To calculate the relationship between fire safety outcomes and whether or not homes are subject to recent fire safety standards, we apply a two-step regression process. The first step calculates propensity scores that reflect the probability of a fire department reporting to NFIRS, in order to account for NFIRS data consisting of voluntary reports rather than a random sample of reports. The second step uses a Poisson regression to examines the correlation between the number of fires per capita and the proportion of a state's housing stock that is built following the adoption of a code that incorporates a particular edition of NFPA 72. Appendix B contains a detailed discussion of the econometric methodology.

²² Homeowners could of course choose to retroactively update or build to more stringent conditions than the code in place at the time of building. If all houses were already built to more stringent conditions than the new code, such that the new code did not affect housing construction, we would expect to find no impact of the code adoption. As our later survey results indicate, many houses in the United States do not follow the latest smoke alarm standards.

²³ We are unable to do a within-state analysis for two reasons. First, individual localities sometimes have additional code requirements beyond the state level, and there is no database documenting how these local codes change over time. This alone does not preclude a local-level analysis, but we would be missing a potentially important source of local-level variation. Second, our data on the number of homes built in any given year are recorded at the state level, meaning we cannot calculate the fraction of local homes built since the enactment of a new state code.

²⁴ While a similar analysis could be done for UL 217, that standard had not changed substantially during our period of analysis. The 2020 update does incorporate significant changes, but because it is so recent data are not yet available on subsequent fire safety outcomes.

Results

The values in Table 4.3 can be interpreted as the estimated percentage change in the number of fires of a given severity following a 1-percent increase in the proportion of homes built since that edition of NFPA 72 was enacted into the building code. For example, the results suggest a 1-percent increase in a state's housing stock built after enacting the 1999 edition of NFPA 72 code is associated with a 0.4-percent increase in the number of fires that spread beyond the building of origin. Similarly, the results suggest a 1-percent increase in a state's housing stock built after enacting the 2010 edition of NFPA 72 code is associated with a 0.2-percent decrease in the number of fires that spread beyond the building of origin. Each cell is a separate stand-alone estimate from a separate regression; the cells are not intended to be summed across rows or columns. None of the estimates in Table 4.3 are statistically different from zero.²⁵

Table 4.3. Estimated Percentage Change in the Number of Fires Following a 1-Percent Increase in Homes Built Since the Listed Code Was Enacted, 2003–2017

Fire Severity (Fire Spread)	1999 Edition	2002 Edition	2007 Edition	2010 Edition
Beyond building of origin	0.4%	0.4%	0.1%	–0.2%
Confined to building of origin	1.1%	1.1%	1.0%	0.7%
Confined to floor of origin	1.1%	1.2%	1.0%	0.6%
Confined to room of origin	1.0%	1.0%	0.9%	0.4%
Confined to object of origin	2.4%	2.5%	2.2%	2.3%

NOTE: None of the results are statistically significant at a 95-percent confidence level when using heteroskedasticity robust standard errors (which are necessary due to heteroskedasticity in this data).

Although our hypothesis was to expect slight decreases in the number of fires per 100,000 homes as a larger proportion of houses are built under the new code regime, the results initially appear to suggest the opposite—that the number of fires of all severities generally increased as the proportion of houses built under new code regimes increased. The increase in low-severity fires (i.e., fires confined to the object of origin) is surprisingly large. An increase in the number of low-severity fires would not be surprising if there was a corresponding decrease in high-severity fires, as that would suggest fires were being reported and extinguished more quickly. However, none of the estimates are statistically different from zero at standard 95-percent confidence levels. Thus we conclude that these standards do not result in measurable changes in the number of fires of any size. Because our data are from 2003–2017, we believe these results

²⁵ Our initial approach looked at the percentage change in the number of fires per housing unit over time, which also found no significant results. While the results presented in Table 4.3 make more precise use of available identifying variation, the results from examining the change in the number of fires per housing unit over time similarly show no statistically significant impact of more houses being built under the new code regime.

suggest the largest reductions in the number of fires occurred earlier, when smoke alarms were first being adopted. Smoke alarms had already become prevalent by the 1990s.

Table 4.4 presents similar results on the percentage change in firefighter injuries per 100,000 homes due to a 1-percent increase in the number of homes built since the code update. Similarly, we find positive but statistically insignificant increases rather than decreases. The change in firefighter fatalities is particularly large, although the baseline count of firefighter fatalities is relatively small, and the estimates are not statistically different from zero. We conclude that there is no measurable relation between the proportion of homes built since recent standards were adopted and the rate of injuries or fatalities caused by residential fires. Again, given the large literature on the safety benefits of smoke alarms, we suspect that these results reflect the largest benefits having occurred earlier in time.

Table 4.4. Estimated Percentage Change in the Number of Reported Injuries or Fatalities Following a 1-Percent Increase in Homes Built Since the Listed Code Was Enacted, 2003–2017

	1999 Edition	2002 Edition	2007 Edition	2010 Edition
Firefighter injuries per 100,000 homes	0.3%	0.3%	0.4%	0.3%
Firefighter fatalities per 100,000 homes	4.5%	6.4%	5.0%	11.6%
Other injuries per 100,000 homes	0.8%	0.9%	1.0%	0.4%
Other fatalities per 100,000 homes	1.3%	1.4%	1.1%	0.9%

NOTE: None of the results are statistically significant at a 95-percent confidence level when using heteroskedasticity robust standard errors (which are necessary due to heteroskedasticity in this data).

Overall, we find no evidence that an increase in the proportion of houses subject to statewide minimum residential building code updates correlates with statistically significant reductions (or increases) in the number of fires, injuries, or fatalities reported to NFIRS. We speculate that these results may reflect the largest gains having occurred prior to the beginning of our data in 2003. Another possible reason that we do not find a statistically significant relationship between state codes and fire safety outcomes could be that local building codes may commonly be more stringent than state codes. If that is the case, changes in state codes would rarely alter housing construction practices, thus explaining the lack of correlation. We have not conducted a thorough analysis of how commonly local codes are more stringent than state codes, so we do not know if this is the case.

Other Analysis of Potential Benefits of Smoke Alarm Standards

Although the results of our two-step analysis suggest that statewide minimum residential building code updates since 2003 have not measurably reduced fires or improved safety outcomes, standards have and may continue to improve well-being in other ways. To gain an understanding of how smoke alarm usage corresponds to the evolution of standards requirements, we included four questions in the early 2020 fielding of RAND’s American

Life Panel (ALP) nationally representative survey. The four yes/no questions included in the survey were

1. Does your primary residence have at least one functioning smoke alarm?
2. [If answered “Yes” to question 1:] Does your primary residence have a functioning smoke alarm on every floor (including the basement, but not including the attic or garage)?
3. [If answered “Yes” to question 1:] Does your primary residence have a functioning smoke alarm in every bedroom?
4. Have you ever disabled a smoke alarm in your primary residence (e.g., removed the batteries) to prevent nuisance alarms?

The results, weighted for national representativeness, are as shown in Figure 4.3.

Figure 4.3. Smoke Alarm Usage in 2020

	Yes	No
Does your primary residence have at least one functioning smoke alarm?	95% (91.7%, 96.9%)	5% (3.1%, 8.3%)
Among those who have smoke alarms: Does your primary residence have a functioning smoke alarm on every floor (including the basement, but not including the attic or garage)?	90% (88.4%, 91.9%)	10% (8.1%, 11.6%)
Among those who have smoke alarms: Does your primary residence have a functioning smoke alarm in every bedroom?	54% (50.6%, 57.4%)	46% (42.6%, 49.4%)
Have you ever disabled a smoke alarm in your primary residence (e.g., removed the batteries) to prevent nuisance alarms?	36% (32.9%, 39.7%)	64% (60.3%, 67.1%)

NOTE: Ninety-five-percent confidence intervals are in parenthesis. The response rates were 2,487 out of 2,488 for Q1, 2,385 out of 2,389 for Q2 (only asked if the respondent answered “Yes” to Q1), 2,386 out of 2,389 for Q3 (only asked if the respondent answered “Yes” to Q1), and 2,484 out of 2,488 for Q4.

As we speculated previously, one reason we find no evidence of benefits from updated building codes may be because earlier adoption of now-widespread practices—such as having a smoke alarm at all—may have already imparted the largest safety benefits. Indeed, results of surveys conducted since the 1970s demonstrate that smoke detectors had rapidly become

pervasive prior to 2003, which is the starting date for data used in our analysis. In fact, the Centers for Disease Control and Prevention (CDC) reported that

the prevalence of smoke detectors in the United States has been steadily increasing since the early 1970s, when only about 5% of households had them. By 1985, an estimated 75% of households had at least one smoke detector. Similarly, during 1978–1984, deaths from house fires dropped more than 30%, from 6,015 to 4,075. This decline is attributed in part to recent home fire safety efforts, including the passage of numerous state laws requiring the installation of smoke detectors. (CDC, 1986)²⁶

A 1985 survey conducted by the CDC found that 76.3 percent of households in DeKalb County, Georgia, owned smoke detectors at the time. The survey is consistent with standards and building codes encouraging smoke detector installation, as dwellings under ten years old were more likely to have smoke detectors than dwellings ten years old or older (89.9 percent versus 71.8 percent) (CDC, 1986).

A later survey conducted by the CDC in 2001–2003 found that 95 percent of U.S. households reported having at least one smoke alarm installed in their home (Ballesteros and Krewsnow, 2007). If most safety gains come from having at least one smoke alarm installed in the home, this suggests that by 2003 there were few further gains to be made on this front.

Indeed, our ALP survey found that 95 percent of respondents reported having at least one functioning smoke alarm in their primary residence. Given the similarity of this result to that of the 2003 survey, it is less surprising that we find little evidence of additional safety gains since 2003. However, we note that while 90 percent of respondents with smoke alarms (85 percent of all respondents) reported having one smoke alarm on every floor, only 54 percent of respondents with smoke alarms (51 percent of all respondents) reported following the most recent standard of one smoke alarm in every bedroom. As the country’s housing stock continues to update over time, we expect this rate to increase due to current standard requirements.

Standards and Nuisance Alarms

Although smoke alarms are now widespread, “nuisance alarms”—smoke alarms being triggered undesirably by events such as by certain cooking activities—are also common. A homeowner might disable a smoke alarm to prevent these nuisance alarms, such as by removing the smoke alarm batteries. Our ALP survey found that more than one-third of households have disabled a smoke alarm to prevent nuisance alarms—a finding that provides compelling evidence that this issue is a concern. Although disabling the smoke alarm stops nuisance alarms, the smoke alarm is no longer providing safety benefits to the homeowner. NFPA studies have found that 17 percent of civilian fire deaths occurred in homes with nonoperational smoke alarms, and that nuisance alarms were the leading cause for disabling smoke alarms (Ahrens, 2004; 2019).

²⁶ See Ahrens (2021) for useful illustrations of trends over time.

As discussed in Chapter 2, NFPA 72 gradually introduced measures to reduce the likelihood of nuisance alarms as the magnitude of this issue became apparent. These measures included limiting how close smoke alarms can be placed to cooking appliances and bathrooms, requiring hush buttons, and prescribing the allowable type of detector technology. These changes—driven by recent NIST research (Cleary and Chernovsky, 2013; Cleary, 2014)—were intended to help reduce nuisance alarms. Any benefits associated with the most recent changes cannot be observed yet, including the impacts of changes to UL 217 that did not come into effect until May 2020 and changes to NFPA 72 that do not come into effect until 2022. When these changes do come into effect, health and safety benefits may accrue if residents disable smoke alarms less frequently.

In addition, the reduction in nuisance alarms in and of itself would provide a public benefit—individuals may value having fewer sudden scrambles to silence the smoke alarm’s ill-timed critique of their cooking skills, a task that is not simplified by the hush button being located on the ceiling. The convenience value of reduced nuisance alarms may be best seen through eventual sales data—if consumers value fewer nuisance alarms, they may be more eager to buy new replacement smoke alarms once models compliant with the new standards are available.

Conclusion

Prior studies have demonstrated the great effectiveness of smoke alarms in reducing the incidence of fire fatalities. Our analysis presents the first examination of the benefits of smoke alarm standards. Because smoke alarm standards are adopted into state residential building codes, we conducted a quantitative analysis to assess the relationship between the proportion of homes built since a code was adopted and several fire safety outcomes. Using data from 2003–2017, we find no evidence that increases in the proportion of houses subject to statewide minimum residential building code updates is correlated with statistically significant reductions (or increases) in the number of reported fires, injuries, or fatalities. We speculate that these results may reflect the largest gains having occurred prior to 2003 and the beginning of our data. Survey data support this view, as by 2003 a full 95 percent of household had already installed at least one smoke detector. Our 2020 survey reached the same results. Together, the literature and these results suggest that smoke alarms—and the research and standards that encouraged their adoption—have had significant effects on health and safety, but that the largest of those impacts occurred prior to 2003. We are unable to identify any statistically significant health and safety impacts imparted through the enactment of updated residential building codes since 2003.

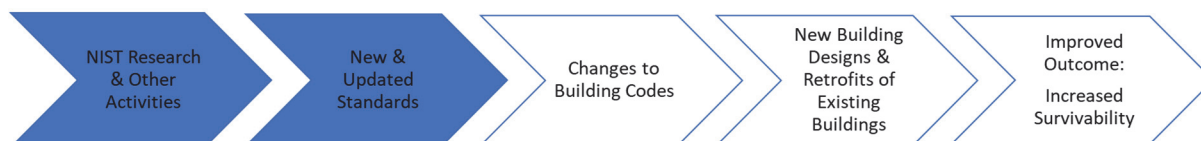
These results do not necessarily mean that further updates to smoke alarm standards or building codes are irrelevant. Ongoing work on smoke alarm standards, supported by NIST research, is now rightly focused on other issues, such as the prevalence of nuisance alarms. Our ALP survey found that more than one out of three households report having disabled a smoke alarm to prevent nuisance alarms. Meaningful improvements in fire safety and general well-being could result if standards—based in part on NIST research—can reduce the frequency with which households disable smoke alarms.

5. Wildland-Urban Interface Standards

Our third case study on the impacts of fire safety standards focuses on standards associated with WUI. Wildland fires are receiving increasing attention from the research community. Whereas many urban fire-related risks have been reduced through research-informed changes to building codes and standards, the risk of WUI fires appears to be growing. Rasker (2018) notes that “wildfires are bigger, burn longer, cause more damage, and kill more people than before.” The increase in WUI risks is driven by both increased wildland fire risk, increased human-caused ignition, and increased building exposure. The result is an increase in fire losses and suppression costs (Rasker, 2018).

To contextualize and organize this discussion, we again use a logic model that charts the path from NIST activities to fire outcomes (Figure 5.1), highlighting the steps that we focus on in this chapter. In this chapter we examine NIST’s role in the development of new WUI standards and codes that are intended to increase building survivability during wildland fires.

Figure 5.1. Logic Model of National Institute of Standards and Technology Activities and Wildland-Urban Interface Standards and Codes



Case Study 3: The National Institute of Standards and Technology’s Role in Wilderness Urban Interface Building Standards and Codes

NIST work on WUI fire research began as an extension of its general fire efforts through the National Fire Research Laboratory. NIST WUI work appears to be motivated in part by large wildland fires that occurred in the 1990s and early 2000s, such as the 1991 Oakland Hills Fire, the 2000 Los Alamos Fire, and the 2002 Hayman Fire (e.g., see Manzello, Cleary, and Yang, 2004). Table 5.1 provides a timeline of relevant NIST program and project efforts on WUI fire research.

According to NIST personnel, early NIST WUI fire research focused on developing a better understanding of how fire spreads from the vegetative fuels of the wildland to structures. Initially, this research examined how fire was spread by flame contact and thermal radiation. However, a growing body of research has shown that firebrands—small flaming or glowing embers that may be transported by the wind into buildings’ cracks or crevices—are another important mechanism of structure ignition in wildfires (e.g., Barrow, 1945; Ramsay, McArthur,

Table 5.1. Timeline of the National Institute of Standards and Technology’s Key Contributions to the Development of Wilderness Urban Interface Standards

Event	Date	NIST Role	Impact
Development of test methodologies and devices to understand ignition from firebrands during WUI fires	2004–present	NIST is developing test methodologies and devices, including the “Dragon” firebrand generator and an “emberometer” that quantifies firebrand exposure	• The ability to generate and measure standardized firebrands, enabling structured laboratory testing of ember behavior and impacts • Improved understanding of the role of firebrands in ignition and the spread of WUI fires
Detailed studies of four WUI fires (including the 2018 Camp Fire)	2007–present	NIST is collecting the data needed to better model fire impacts and WUI fire impacts	• Informs WUI mitigation efforts and building standards
Fire Risk Reduction in Communities Program	2011–present	NIST is combining lab- and field-scale experiments with computer fire models to characterize WUI fire exposure	• Supports the development of science-based standards, codes, and practices for fire resistant communities

and Dowling, 1987; Leonard and McArthur, 1999). By 2004, NIST researchers began researching how firebrands can cause structure ignition in WUI fires (Manzello, Clearly, and Yang, 2004). Subsequent full-scale experiments and reconstructions of actual fire incidents by NIST and others demonstrated that a majority of structure ignitions were caused by firebrands rather than flame contact and thermal radiation (Manzello et al., 2018, p. 64). Gaps in knowledge about firebrand ignition of structures, coupled with the observed risk, have led NIST to focus WUI fire research on understanding how firebrands ignite structures (Hamins et al., 2012, pp. 59, 91) and the development of test methods and apparatuses, such as the NIST “Dragon,” which generates standardized firebrands for use in tests.

Another line of effort is collecting data on historic fires, typically in the immediate aftermath of the fire when data are best available. A NIST project called the “WUI Fire Exposure Data Collection and Modeling Project” began in 2011 to organize these efforts (NIST, 2018a) and has led to publications such as a case study of timelines, impacts, and identification of risk factors for building ignition during the Witch and Guejito Fires in the Trails subdivision near San Diego, California in 2007 (Maranghides et al., 2013), a study of the fire behavior and WUI measurement science of 2011 fires in Amarillo, Texas (Maranghides et al., 2011), and a case study of the impact of the Waldo Canyon Fire in the Mountain Shadows Community of Colorado Springs in 2012 (Maranghides et al., 2015). NIST has been continuing this work through a study of the 2018 Camp Fire near Paradise, California, and plans to release five reports focusing on topics such as the progression of the fire, the evacuation effort, defensive actions, and the survivability of structures (Maranghides et al., 2021a). This body of work has led to important new research in collaboration with the California Department of Forestry and Fire Protection (CAL FIRE), IBHS, and the California Building Industry Association on structure-to-structure fire spreading (Maranghides et al., 2021b).

NIST has conducted a variety of other complementary research on the socio-technical aspects of WUI risk. For example, NIST has developed a fire and ember exposure scale (Maranghides and Mell, 2013) that could eventually evolve to be incorporated into building codes so that code requirements can be based on WUI fire risk (Maranghides and Mell, 2013). NIST has also conducted research on the economics of WUI fires, such as an exploration of WUI fire trends and economic impacts using NFIRS (Thomas and Butry, 2012).

NIST has been leading several efforts that seek to increase outreach about WUI fire and coordinate efforts across the research community. NIST established the Fire Risk Reduction in Communities Program, which aims to conduct research to “improve the resilience of wildland-urban interface communities,” make improvements to firefighting, and fund related research through grants (NIST, July 2021). Further, NIST has sponsored or co-sponsored at least four workshops on WUI fires.²⁷ NIST personnel also collaborate with non-NIST researchers on WUI research.²⁸

NIST’s work is providing key fundamental groundwork needed to develop evidence-based WUI standards. For example, IBHS has adopted WUI-related infratechnologies developed by NIST to conduct research on how effectively different building designs and materials deter firebrand-driven ignition. Most notably, the ten firebrand generators used during IBHS experiments are based on the design of the NIST Dragon, with modifications to automate fuel delivery (Standohar-Alfano et al., 2017, p. 14). To motivate the need for the research, IBHS cites surveys conducted by NIST after the Witch Fire, which showed that firebrands were a frequent source of ignition, as well as other NIST research outlining firebrand research needs (Standohar-Alfano et al., 2017, p. 3). IBHS also compared the firebrands created in their facility with those documented by NIST testing (Standohar-Alfano et al., 2017, p. 16).

Table 5.2 provides a timeline of the most relevant WUI-related standards and codes for building design. This timeline is based on the codes produced by WUI-related committees as well as the NIST *Strategic Roadmap* (Hamins et al., 2012). Codes and standards for WUI firefighting also exist, but they are outside this study’s focus on standards for risk prevention and mitigation of WUI fires. It is important to note that the line between WUI-related fire standards and codes and non-WUI fire standards and codes is not always clear—many codes designed for general fires will also be applicable to WUI fires. Therefore, our scope was guided by the codes and standards under the jurisdiction of the WUI-related committees.

²⁷ The workshops were Innovative Fire Protection (2009; WUI was one track of this workshop, which appears to have informed the NIST Fire Research Roadmap [Hamins et al., 2012]), Wildland Urban Interface Fire Research Needs (2012), Structure Ignition in Wildland-Urban Interface (WUI) Fires (2016), and Large Outdoor Fires and the Built Environment (2017).

²⁸ For example, NIST researcher Nelson Bryner served on a project technical panel for a 2015 Fire Protection Research Foundation study called *Pathways for Building Fire Spread at the Wildland Urban Interface* (Gollner et al., 2015).

Table 5.2. Timeline of Key Wilderness Urban Interface Codes

Time	Activity
1956–1998	Publication of Community Forest Fighting Equipment (NFPA-295) (NFPA, 2017b; undated b) The standard was targeted to fire departments that control wildfires and included requirements for fighting wildland fires as well as an increasing emphasis on preventing fires over the years. It was renamed Community Equipment and Organization for Fighting Forest, Grass, and Brush Fires in 1956, Recommendations for Forest, Grass, and Brush Fire Control in 1965, Standard for Wildfire Control by Volunteer Fire Departments in 1973, and Standard for Wildfire Control in 1985. This standard was incorporated into NFPA 1143 in 2003.
1935–1985	Publication of Fire Protection and Prevention for Summer Homes in Forested Areas (NFPA-224) (NFPA, 2017c) This standard focused on requirements for structures and other development (e.g., camps) in forests. In 1953 it was renamed Fire Prevention Standards for Homes and Camps in Forested Areas, in 1962 it was renamed Recommended Good Practice for Homes and Camps in Forest Areas, and in 1972 it was renamed Standard for Homes and Camps in Forest Areas. It was incorporated into NFPA 299 in 1991, which was incorporated into NFPA 1144 in 2002.
1985–2018	Publication of Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas (NFPA-1141) (NFPA, 2017a) This standard focuses on issues beyond structures. It includes geographic issues and fire protection for WUI (e.g., roads, building separation, water supply, fire protection, emergency preparedness). Work on the standard began in 1972 but ran into obstacles so a draft 1977 version was never issued. Over the years, requirements have shifted between this standard and NFPA-1144. NFPA plans to incorporate this standard into NFPA-1140 in the future.
1991, 1997	Publication of Standard for Protection of Life and Property from Wildfire (NFPA-299) (NFPA, 1997) This standard focuses on building and land use standards for properties that might be threatened by wildfire. It incorporated requirements formerly in NFPA-224. NFPA-299 was withdrawn in 2002 and integrated into NFPA-1144.
1996, 2000	Publication of the International Fire Code Institute (IFCI),^a Urban-Wildland Interface Code (Natural Hazards Center, 1996; ICC, 2014, p. iii) The Urban-Wildland Interface Code Committee was convened in 1994. It released its initial code in 1996 and updated it in 2000. ICC obtained full rights to the code through ICBO, and the 2000 version of the code forms the basis of the ICC code released in 2004 (see below).
2002–2018	Publication of Standard for Reducing Structure Ignition Hazards from Wildland Fire (NFPA-1144) (NFPA 2018b) This standard focuses on requirements for new structures in WUI areas and assessments of WUI hazards. In 2002, NFPA-299 was renumbered NFPA-1144. NFPA plans to incorporate this standard into NFPA-1140 in the future.
2003–2018	Publication of Standard for Wildland Fire Management (NFPA-1143) (NFPA, 2018a) The standard focuses on both wildland fire suppression and wildland fire management (e.g., prevention or remediation of fire risk.) In 2003, NFPA-295 was renumbered NFPA-1143. NFPA plans to incorporate this standard into NFPA-1140 in the future.
2003–present	Publication of the International Wildland-Urban Interface Code (IWUIC) by ICC The effort began by the ICC in 2001 with three of its members: Building Officials and Code Administrators International, Inc., ICBO, and Southern Building Code Congress International. The goal was to “bridge the gap between enforcement of the International Building Code and International Fire Code by mitigating the hazard of wildfires through model code regulations, which safeguard the public health and safety in all communities, large and small” (ICC, 2014, p. iii). IWUIC is a model code providing requirements for land use and the built environment in WUI areas. The code has been enforced or adapted by jurisdictions in 18 mainly western U.S. states. (ICC, 2019) The code has been updated every three years (2003–2018). It has utilized technical content from <i>2000 Urban-Wildland Interface Code</i> (IFCI, 2000).

Time	Activity
2005–present	California Building Code Chapter 7A, “Materials and Construction Methods for Exterior Wildfire Exposure” (State Fire Marshal, 2007)^b The California Building Standards Commission adopted Chapter 7A in September 2005. It “establishes minimum standards for the protection of life and property by increasing the ability of a building to resist flames and burning embers generated by wildfires” (Quarles and Kearns, 2007, p. 2). It amended the 2001 California Building Code and applied to any new buildings permitted within a very-high Fire Hazard Severity Zone in Local Responsibility Areas as well as buildings in all Fire Hazard Severity Zones in State Responsibility Areas (i.e., unincorporated areas not managed by the federal government). It also applies to remodels of older homes in some local jurisdictions. Requirements for roofing and attic ventilation applied to all homes permitted on or after December 1, 2005, while all the requirements applied to any building permitted on or after July 1, 2008 (2016 version, 701A.3.1). Chapter 7A was released as an emergency supplement to the building code on June 21, 2006. The California Building Code has been updated every three years, recently between 2007 and 2016. In addition, the California Fire Code has a short chapter, Chapter 49, “Requirements for Wildland-Urban Interface Fire Areas”, with requirements for WUI areas. It references California Building Code Chapter 7A and also includes requirements for fire hazard severity zone mapping and vegetation and fuel management (California Building Standards Commission, 2016). The California Fire Code is based largely on the ICC’s <i>International Fire Code</i>.
Future	Publication of Standards for Wildland Fire Safety (NFPA-1140) (NFPA, undated c) NFPA plans to consolidate all future revisions of wildland fire codes (NFPA-1141, NFPA-1143, and NFPA-1143, discussed above, as well as NFPA-1051, Standard for Wildland Firefighting Personnel Professional Qualifications) into a single edition.

NOTES:

^a IFCI was set up in 1991 by the Western Fire Chiefs Association, ICBO, and the International Association of Fire Chiefs. ICBO served as one of the founders of ICC in 1994. The 1990s was a turbulent decade for SDOs, especially for fire codes. In 1997, ICC and NFPA agreed to collaborate on fire codes, but by 1999 the agreement had ended in lawsuits between the two organizations and realignments of them. In the aftermath ICBO acquired full rights to IFCI codes, and IFCI apparently ceased to exist (Reckner, 1999; Schepel, 2005, p. 155).

^b The NIST Roadmap (Hamins et al., 2012, p. 103) refers to “Chapter 86B” of the “California State Fire Code,” called “Material and Construction Methods for Exterior Wildfire Exposure.” The fire code does not have an 86B, so it appears that NIST is referring to the building code.

In addition to SDO standards and model building codes, NIST personnel have recently worked or are working on two other efforts to expand the reach of WUI standards and codes. NIST personnel, including Alexander Maraghides, Erica Kuligowski, and Nelson Bryner provided technical support for the development and implementation of Executive Order (EO) 13,728, Wildland-Urban Interface Federal Risk Mitigation (Obama, 2016). The EO requires newly constructed or altered buildings over 5,000 gross square feet within a WUI that are owned by federal agencies to adhere to the IWUIC or equivalent code. In addition, agencies must conduct a wildfire risk assessment of their existing buildings over 5,000 gross square feet within a WUI and are encouraged to bring such buildings into compliance with codes.

Development of the EO occurred in the National Security Council–organized Sub-Interagency Policy Committee on Increasing the Resiliency of Communities and Federal Assets in the Wildland-Urban Interface. NIST researchers made presentations at committee meetings on the current state-of-the-art building and fire codes as applied to WUI, led the technical discussions, and assisted in drafting proposed language for the EO.

After this EO was issued, NIST staff continued to serve on the subsequent implementation plan through the Mitigation Framework Leadership Group. This group developed implementation

guidelines to advise and assist agency compliance with the code requirements and provided assistance to the agencies in interpreting the implementing guidelines (Mitigation Framework Leadership Group, 2017).

NIST researchers have been leading a second effort with the ISO. In October 2018, Samuel Manzello presented at ISO meetings and helped to host workshops, including a workshop at the ISO Technical Committee (TC) 92 plenary meetings in Delft, Netherlands (Manzello, 2019a). As a result of these activities, ISO/TC 92/TG3 proposed and approved the formation of a new working group, ISO TC92/WG 14, “Large Outdoor Fires and the Built Environment,” with Manzello as the convener.

Participation in Standards Development Organizations

NIST research and the participation of NIST researchers on WUI-oriented SDO committees has influenced those SDO’s efforts since at least the late 1990s. Past NIST work specifically focused on WUI codes and standards by leveraging NIST researcher participation on SDO committees and sharing NIST research results in forums such as NIST-led workshops.

According to NIST and our review of SDO documentation, NIST WUI researchers are members and active participants of several WUI-related SDO committees.²⁹ Table 5.3 summarizes NIST involvement in these committees.

An important step in developing WUI standards is the development of standardized test methods, which serve two important purposes. First, they provide a systematic and objective way to assess and compare the performance of materials and processes. This is important for the WUI setting, where the extent of structure damage depends on many interdependent variables. The second important purpose of standardized tests is to certify that products comply with standards.

NIST has played an important role in the development of several standardized test methods, including ASTM E2886, “Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement” (ASTM, undated e). California’s Chapter 7A initially “recommended that a metal mesh of 6 mm be placed behind building vents to prevent firebrand entry into structures,” although “the mesh size was not based on any scientific testing since no test methods were available at that time” (Manzello, 2014). Subsequent research by NIST utilizing standardized test methods showed that this mesh size would be ineffective, and NIST researchers worked with CAL FIRE to revise the code to be more effective at reducing firebrand entry into structures (Manzello, 2014).

Similarly, ASTM WK23700, “New Test Method for Evaluating Roof Field Vent Response to Wind Blown Flame and Burning Ember Exposure” (ASTM, undated f) uses an ember generator based on NIST’s Dragon design for evaluating the performance of ridge and off-ridge through-roof vents.

²⁹ NIST, 2017b.

Table 5.3. The National Institute of Standards and Technology’s Involvement in Wilderness Urban Interface Standards Development Organization (and Related) Committees

Organization	Standard(s)	Committee	Role(s)	Category	Time Period
NFPA	Various	Wildland Fire Technical Committees ^a	Principal and alternate	R/T (Applied Research/Testing Laboratory)	1997–present
CAL FIRE	California Code of Regulations, Title 24, Part 2, Chapter 7A, “Materials and Construction Methods for Exterior Wildfire Exposure”	Wildfire Protection Building Construction Task Force	Member	N/A	2010–present ^b
ICC	International Wildland-Urban Interface Code (IWUIC)	Fire, Performance, Wildland-Urban Interface Code Interpretation Committee (FCIC) ^c	Member	N/A	2015–2017 ^d
ASTM	Various standards	Subcommittee E05.14 on Quantification of Exterior Fire Exposures	Member	N/A	As of 2019 ^e
ISO	N/A (technical report in development)	ISO Technical Committee 92 Working Group 3 (ISO/TC 92/WG 14) on Large Outdoor Fires and the Built Environment	Convener (leader)	N/A	2019–present

NOTES:

^a The names and scope of the NFPA committees have changed frequently throughout NFPA’s history; this table reflects the committee names as of 2021. Committee names, responsibilities, and membership are located on the NFPA website (NFPA, undated d). Alexander Maranghides is NIST’s representative to the Wildland and Rural Fire Protection Committee and the Wildland Fire Management Committee, and Nelson Bryner is the alternate.

^b Samuel Manzello participated in a CAL FIRE task force in 2010 (Manzello, 2014). According to correspondence with NIST in 2019, Manzello is on the Wildfire Protection Building Construction Task Force and Alexander Maranghides is the lead NIST representative on the most recent Chapter 7A TG.

^c FCIC is referenced on the ICC website but does not contain committee documentation or current or historical interpretations (ICC, undated a).

^d Nelson Bryner was a member of the 2016–2017 FCIC (ICC, 2016), but NIST was not represented on the committee as of 2018 (ICC, 2018). In addition, Bryner was a member of the ICC’s International Building Code Fire Safety Code Committee (ICCI, 2018).

^e As of 2019, Samuel Manzello on this committee. We were unable to find committee rosters to determine the history of NIST involvement.

Conclusion

The development of WUI standards is much more nascent than the development of smoke alarm standards. One reason for this may be that the ability to precisely measure and monitor the factors that cause WUI fires has only been recently developed, in large part due to research conducted by NIST. The improved understanding of how WUI fires spread and precisely how affected buildings become damaged is leading to new approaches and standards for protecting buildings from WUI fires. In the next chapter, we examine the WUI benefits associated with ongoing improvements to standards.

6. The Economic Impact of Wildland-Urban Interface Safety Standards

This chapter examines the impacts of WUI standards and codes on societal well-being. As illustrated in Figure 6.1, these changes in building design can lead to increased survivability of buildings during wildland fires, thereby reducing economic damage caused by the fire and possibly saving lives. As in our analysis of smoke alarm standards, this high-level logic model guided our analysis of the economic impacts of safety standards focused on WUI.

Figure 6.1. Logic Model of the National Institute of Standards and Technology’s Activities and Wildland-Urban Interface Standards and Codes



Estimating the causal impact of standards and codes in reducing wildfire damages, injuries, and fatalities is difficult for several reasons. First, compliance with and enforcement of building codes may vary. Second, it is not always clear what proportion of new homes would already be compliant regardless of the code change.³⁰ Third, changes in codes rarely require retroactive changes to existing structures, and the long lifetime of infrastructure means that it can take decades before new codes are universally implemented. For example, as discussed in Chapter 3, 5 percent of homes still did not have smoke alarms in 2020.

Standards and codes can also have economic impacts beyond the prevention of damages and injuries or fatalities. Vaughan and Turner (2013) assert that building codes can “accelerate innovation because they create markets for products at and above the current code.” For example, when language requiring that vents “resist the intrusion of flames and embers” was added to Chapter 7A of the California building code (State Fire Marshal, 2007, p. 258), such vents did not exist. This is admittedly a double-edged sword, as changes in codes could impose additional costs on the construction of new buildings.

³⁰ Further, changes to code do not always involve increased restrictions or additional mandates. Sometimes changes to code relax previous requirements.

In Chapter 5, we reviewed NIST activities that help establish the effectiveness of design changes in protecting homes during wildfires. Such research is still in its early stages, so the effects of potential design changes on survivability are highly uncertain. To inform the potential impacts of future changes to WUI standards and codes, this chapter examines the extent to which houses built during more recent code regimes are better able to survive wildfires. Specifically, we examine the association between the adoption of Chapter 7A of the California Building Code and survivability of homes during the 2018 Camp Fire in Paradise, California. Chapter 7A of the California Building Code mandates certain specific design features (e.g., adoption of smaller vent screen mesh) in homes located in particular areas, including Paradise, that are at high risk for wildfires.³¹ The Camp Fire, although only a single fire, is a useful case study because it has more data on building survivability than prior wildfire incidents.

Our analysis provides strong evidence that newer homes were more likely to survive the Camp Fire than older homes. However, we were unable to find evidence that directly links survivability to California Building Code Chapter 7A. Studies of buildings affected by wildfires typically collect minimal information on undamaged buildings, making it impossible to compare the design of buildings that ignited with those that survived. Collection of such data could greatly improve the development of WUI standards identifying specific building designs that support housing survivability in wildfires.

Previous Studies of Wildland-Urban Interface Building Survivability

This study builds on two recent efforts to understand the survivability of buildings to WUI fires.

Syphard and Keeley (2019) estimated the effects of different building design features (e.g., vent screen mesh, eave construction) for fires in California between 2013 and 2018. They used data collected as part of the CAL FIRE Damage Inspection (DINS) program, which inspects buildings damaged during wildland fires and collects data about damage extent, building features, cause of ignition (when possible), and defensive measures (see Henning, Cox, and Shew, 2016).

Syphard and Keeley analyzed data for fires that resulted in destroyed structures across 36 California counties. The dataset is dominated by the 2018 Camp Fire, which accounts for nearly half of the 41,717 damaged structures analyzed in the study. They compared the efficacy of different structural features and concluded that eave construction was most critical for explaining

³¹ Chapter 7A applies to new construction of most building types in very high Fire Hazard Severity Zones in Local Responsibility Areas and all Fire Hazard Severity Zones (also including moderate and high) in State Responsibility Areas that are outside of municipalities. Municipalities (i.e., “cities and other local agencies,” as described in Chapter 7A [State Fire Marshal, 2007]) have latitude as to which areas are designated Fire Hazard Severity Zones where Chapter 7A is enforced.

survivability (i.e., closed eaves are more survivable than open eaves). Multipane (rather than single-pane) windows were also important, while the importance of other factors such as exterior siding and vent screens varied across California regions. However, a major limitation of the CAL FIRE DINS data is that they survey only structures that were damaged or destroyed by the fires. Therefore, Syphard and Keeley's analysis cannot account for structural features that may have led to a complete avoidance of visible fire damage.

In an effort to assess the impacts of California Building Code Chapter 7A, reporters from the *Sacramento Bee* (Kasler and Reese, 2019) used CAL FIRE DINS data as well as data about undamaged structures from the Butte County Assessor's Office. Kasler and Reese compared the survivability of single-family houses that were built before 2008, when the requirements from Chapter 7A took full effect, with those built during or after 2008. They found that 51 percent of the homes built during or after 2008 were undamaged versus only 18 percent of the homes built prior to 2008.

The Kasler and Reese analysis is illuminating since it used a large number of observations from a complete population of structures. An important limitation of their analysis is that it does not account for factors potentially associated with home age other than Chapter 7A, which may account for the difference in survivability. In this chapter we expand upon the work done by Kasler and Reese to increase our understanding of the potential impacts of changes to WUI building codes on the survivability of houses in the Camp Fire.

Camp Fire Case Study

Data Overview

Our analysis used the same CAL FIRE DINS and Butte County Assessor's Office data used by Kasler and Reese (2019).³² We restricted our analysis to single-family houses because these homes tend to be the primary focus of recent WUI standards and code activities, although other types of new construction, such as multifamily and commercial, are also subject to the requirements of Chapter 7A. Chapter 7A first came into force on December 1, 2005, for building components related to roofing and attic ventilation. The remainder of the code came into force on January 1, 2008, in State Responsibility Areas (outside of municipalities) and on July 1, 2008, for participating municipalities (i.e., areas designated as very high Fire Hazard Severity Zones in Local Responsibility Areas). Per CAL FIRE data, the fire perimeter area is nearly all subject to Chapter 7A, with exceptions for federal lands and pockets of high-hazard zones within Paradise

³² The web mapping application is located at CAL FIRE (undated a). In addition, data feeds are publicly available from ArcGIS feature dataservers at ArcGIS REST Services Directory (undated a) (for undamaged structures) and ArcGIS REST Services Directory (undated c) (for damaged structures). We used the data assembled and graciously provided by Dale Kasler and Phillip Reese of the *Sacramento Bee*.

municipal boundaries.³³ We included both manufactured homes and permanent homes in our analysis. Manufactured homes, which are also known as prefabricated or mobile homes but exclude modular homes, often share similar design features with permanent homes and are interspersed with permanent homes in the Paradise area. Though state and local building codes typically do not apply to manufactured homes, which are regulated by the federal government,³⁴ Chapter 7A applies to all manufactured homes built after September 1, 2008 that are installed in areas subject to Chapter 7A.³⁵

In addition, we obtained a CAL FIRE map of the fire perimeter.³⁶ During the course of a fire, fire perimeter maps are updated on at least a daily basis and are likely to contain significant errors, especially in remote areas where smoke and unburned canopies may obscure aerial views (see Kolden and Wiesberg, 2007, pp. 23–24, 29–30). Errors in the fire perimeter seem less likely once the fire has been contained, especially in developed areas, where houses are closely inspected. Upon our initial analysis of the fire perimeters and structures, it was clear that the undamaged structure dataset included structures in unburnt areas outside the fire perimeter. We excluded these structures from our analysis. We also excluded all houses built prior to 1901.³⁷ Table 6.1 summarizes the 15,486 houses included in our analysis.

Degree of Damages Incurred During the Camp Fire

As shown in Table 6.1, not all homes suffered the same degree of damage during the Camp Fire. Figure 6.2 shows a histogram of the number of homes built in each year, grouped by the level of damage. Figure 6.3 shows the change in damage rates over time. Several features of the data stand out. First, survivability has been increasing over time, particularly between the 1970s and 1990s. Second, there is not a clear step in 2008 as might be expected if the implementation of Chapter 7A had a sudden impact on the survivability of houses built in 2008 and later. However, relatively few homes were built after 2008, which make estimates of damage rates more difficult and hence measuring the impact of Chapter 7A more challenging. Third, most of

³³ According to CAL FIRE maps, nearly all of Paradise (a Local Responsibility Area) and all of Magalia and areas to the east of Paradise are designated as Very High Fire Hazard Severity Zones; the remainder of the Camp Fire perimeter (areas to the south and southwest) is split between high and moderate fire hazard severity zones (Office of the State Fire Marshal, undated).

³⁴ 42 U.S.C. 70 regulates manufactured homes throughout the United States. The Department of Housing and Urban Development through its Office of Manufactured Housing Programs is responsible for developing the Manufactured Home Construction and Safety Standards (24 C.F.R. 3280).

³⁵ See California Department of Housing and Community Development (2012).

³⁶ The CAL FIRE Camp Fire perimeter map was obtained from ArcGIS REST Services Directory (undated b). In addition, perimeter maps for a large number of historic fires are available from CAL FIRE (undated d).

³⁷ Some houses show a year built value that was missing (355 houses), zero (122), 1900 (532), or between 1 and 1,860 (8). Assuming that many of these values may be invalid, we excluded all houses for which the year built is recorded as before 1901.

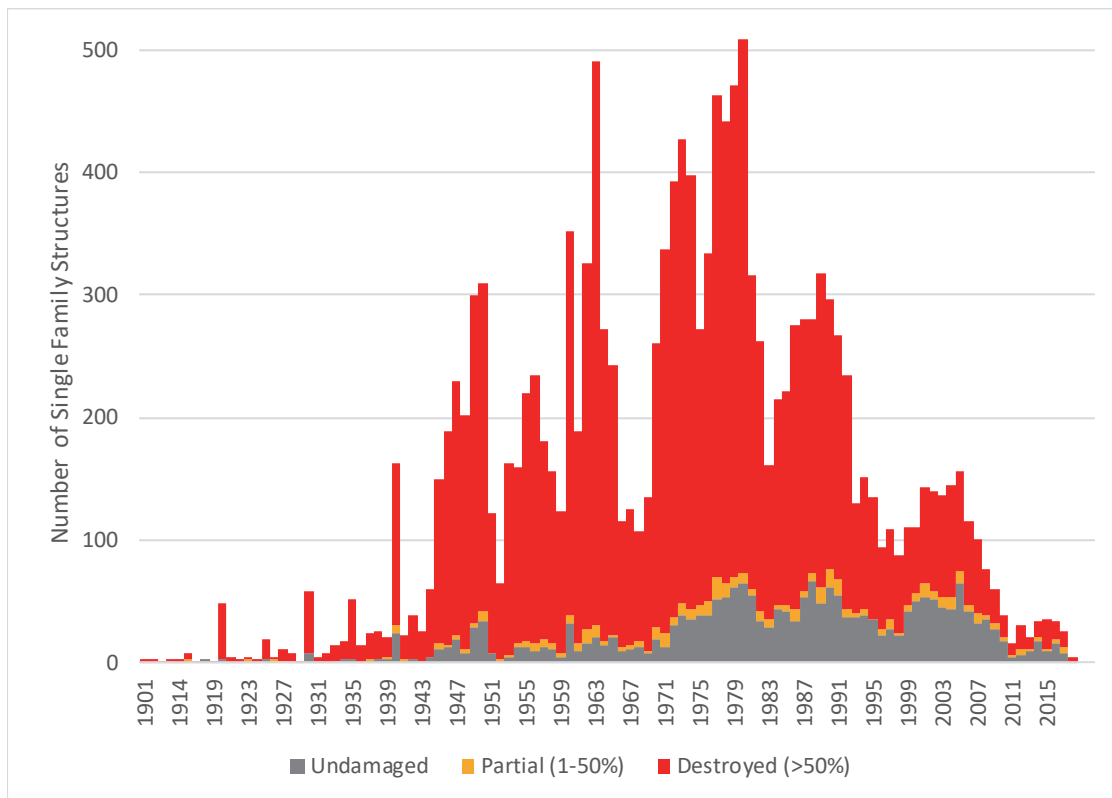
the homes were either undamaged or destroyed. Very few homes had partial damage, most likely because the speed of the fire made it impossible to suppress house fires once they had ignited.

Table 6.1. Counts and Damage Levels of Houses in the 2018 Camp Fire

	Year Built	
	Before 2008	2008 or Later
Permanent homes: undamaged	1,790	138
Permanent homes: partially damaged	401	31
Permanent homes: destroyed	9,525	143
Permanent homes: total	11,716	312
Manufactured homes: undamaged	216	9
Manufactured homes: partially damaged	27	2
Manufactured homes: destroyed	3,155	49
Manufactured homes: total	3,398	60

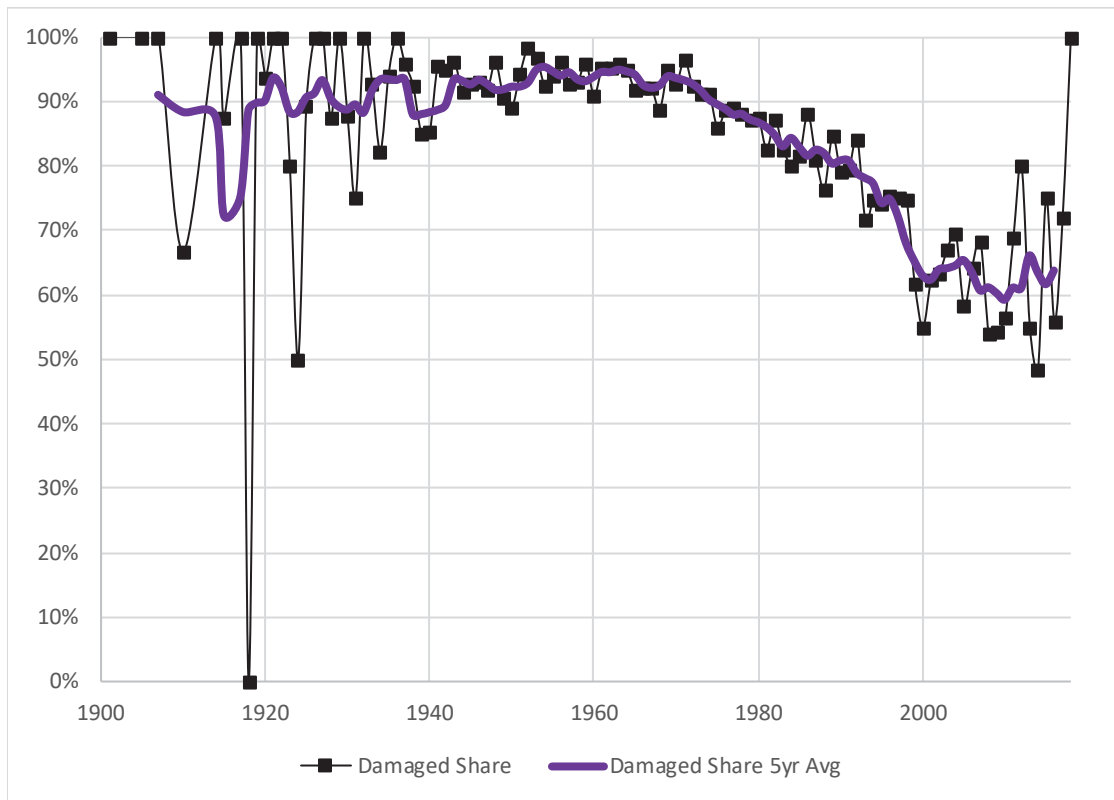
NOTE: Partial damage includes houses assessed as affected (1–9 percent damage), minor damage (10–25 percent), and major damage (26–50 percent)

Figure 6.2. Level of Damages in the 2018 Camp Fire for Homes Built in Each Year



NOTE: Partial damage includes houses assessed as affected (1–9 percent damage), minor damage (10–25 percent), and major damage (26–50 percent).

Figure 6.3. Share of Damaged Homes in the 2018 Camp Fire for Homes Built in Each Year



NOTE: Five-year average is calculated based on the number of homes built in each year and the two years before and after that year.

The results in Figure 6.3 show that newer homes generally survived at higher rates than older homes—which is consistent with newer building techniques that improve survivability. For example, newer houses seem more likely to have double-paned windows, which likely increases survivability to fires. According to the DINS data from the Camp Fire, whereas about half of damaged homes built during the 1940s had multipane windows, that figure rose to around 80 percent of homes built in 2000 or later. Syphard and Keeley (2019) estimated that damaged homes with multipaned windows were about 94 percent as likely to be heavily damaged than homes without them. However, because the data on undamaged homes do not include information about these features, it is not possible to fully ascertain their impacts. Therefore we use year built, which is observed for all homes, as a proxy for general improvements to building techniques.

Even if the improvements in survivability in newer houses are caused by improvements in building design, such improvements may or may not have been brought about by changes in codes and standards. Figure 6.3 shows relatively steady improvement in survivability beginning with houses built in the early 1970s, with the biggest jump in survivability occurring among houses built after the late 1990s, all well before Chapter 7A came into effect.

Factors That May Confound the Perceived Relationship Between House Age and Survivability

A major limitation of the previous analysis is that building age may be correlated with factors that affect survivability beyond building construction or design. Factors such as topography, vegetation, and housing density (which can depend on lot size) all affect the probability of a home's survival, and these factors may also be correlated with the year a home was built. The analysis from the previous section might show a correlation between survivability and the age of houses even if there is no relationship between building construction or design and survivability. This section shows that there are indeed correlations between house age and other important risk factors.

Building age is not distributed randomly within the fire perimeter. Figure 6.4 shows how house age varies, while Figure 6.5 shows how the diversity of age varies in 250 m radius pixels. Housing in the center of Paradise is diverse in its age, having been built throughout the 1900s and 2000s. Housing in some cells in Paradise and eastern Magalia represent up to nine different decades of housing construction. The southern half of Magalia is a master-planned community developed starting in the late 1970s. Areas on the periphery of Paradise—as well as those in many isolated areas outside of Paradise—are typically newer, with an average year built in the 2000s. Also, in a few areas on the periphery of Paradise, the average year built is as early as the 1930s. These isolated areas tend to be less diverse in age and have lower densities.

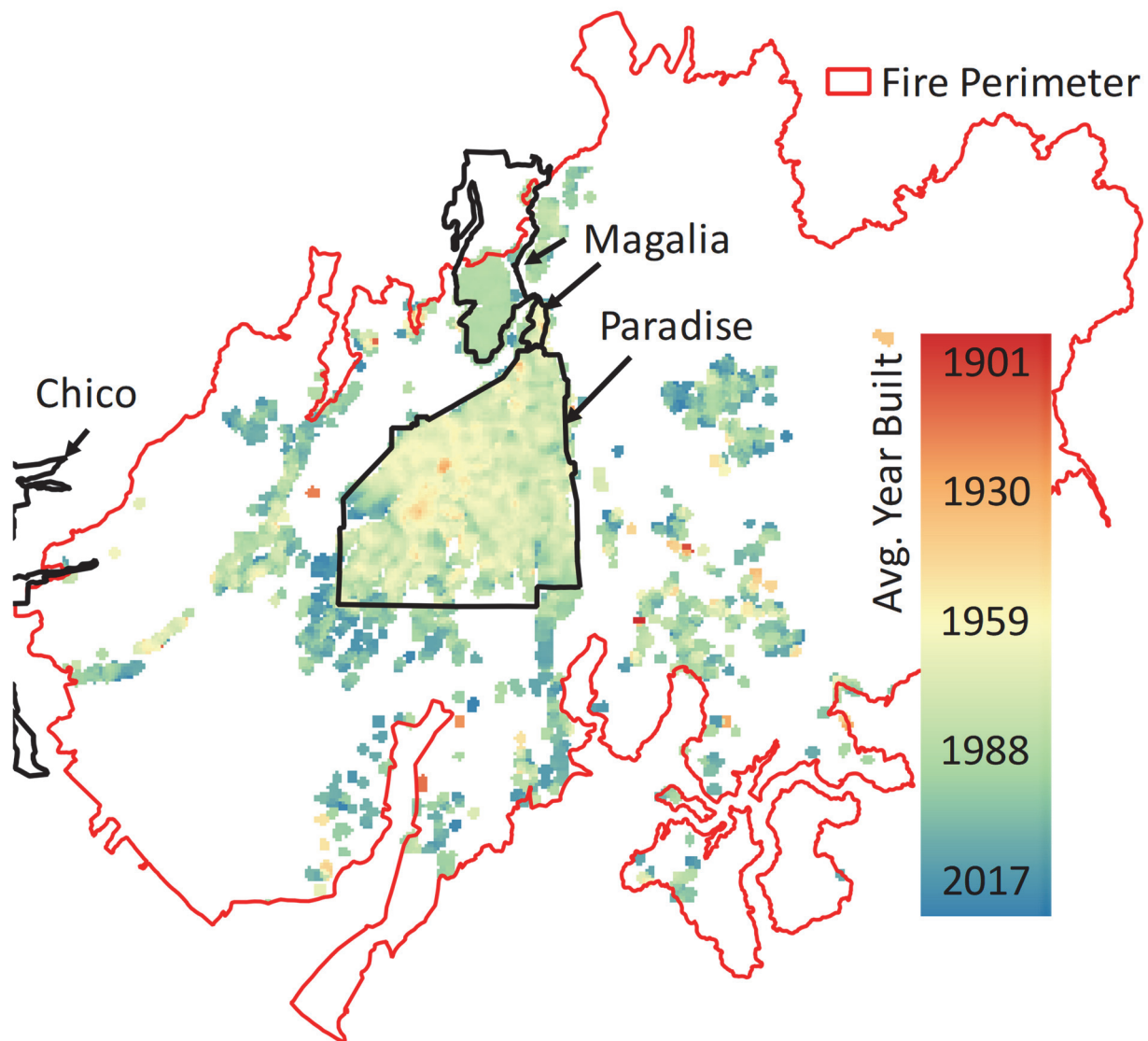
Because house age is not randomly distributed within the fire perimeter, housing age is correlated with other potential risk factors that are also not randomly distributed within the fire perimeter. If these risk factor affect areas with older homes more than areas with newer homes, then the age of housing may be falsely perceived as determining survivability. For example, vegetation and topography vary throughout the affected areas (Rocchio, 2019). Forest dominates the northeast of the fire perimeter, grasses the west, while Paradise straddles a mixture of the two as well as shrubs and developed areas. If newer housing tends to be in areas with more fire-resistant vegetation or topography,³⁸ building age may appear to be driving increases in survivability when survivability is actually being driven by these unobserved factors.

Fire behavior may also confound the analysis of increased survivability. Fires vary in intensity throughout the fire perimeter. During the Camp Fire some areas (especially within Paradise) were subject to extensive spotting ignitions, likely from firebrands blown from the

³⁸ The U.S. Forest Service (Dillon, 2018) has constructed a Wildfire Hazard Potential index for the United States based on simulations of the likelihood and intensity of fires. Magalia and the surrounding area are largely assessed to be very high risk, while most of Paradise is high to very high risk. Areas directly east and west of Paradise, where many of the more isolated homes tend to be located, are largely assessed as moderate risk. CAL FIRE's Fire and Resource Assessment Program ratings are similar, with Paradise, Magalia, and areas to the north and east being dominated with "very high" hazard areas while areas to the south and west being dominated with "high" and "moderate" hazard areas (see CAL FIRE, undated c).

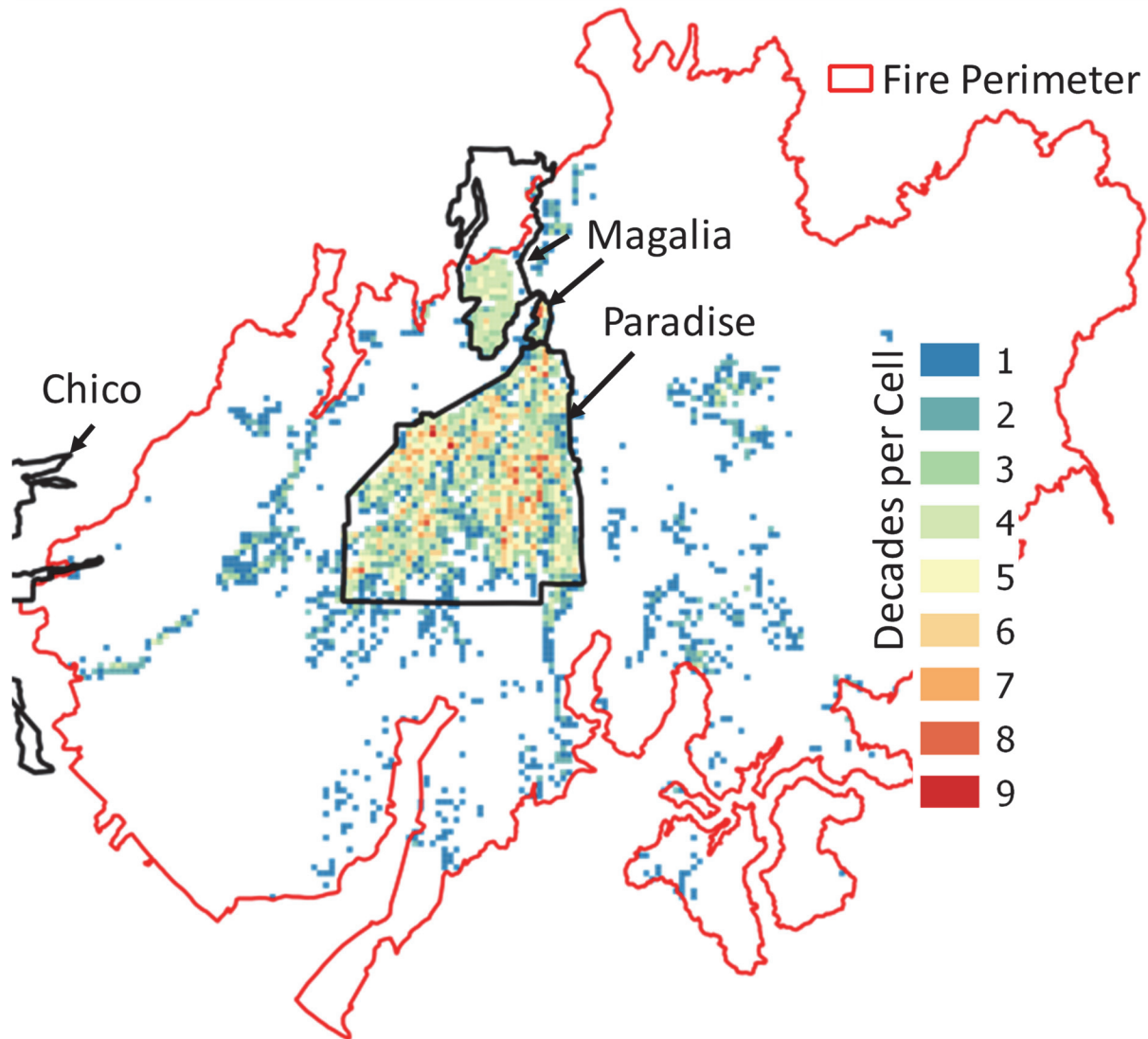
main fire and burning structures (Rocchio, 2019). If this fire behavior was correlated with the age of structures (e.g., if newer subdivisions outside of Paradise experienced less intense fire than older subdivisions within Paradise), it would appear that older houses were less survivable than newer houses, even if the fire's behavior was driving survivability.

Figure 6.4. Average Year Built for Single-Family Homes



NOTE: The average year built is calculated using moving average of year built of single-family homes within 250 m using the "Grid (Moving Average)" tool in QGIS. The tool creates a grid where each pixel is approximately 125m and calculates the average year built in the 250 m radius around that pixel. Areas in white do not have any single-family homes within 250 m.

Figure 6.5. Number of Decades Represented by the Year Housing was Built



NOTES: Houses were mapped to a 250 m grid. Grid cells without houses are white.

Density is another potential driver of survivability that may be correlated with house age. NIST laboratory research has shown experimentally that decreasing the distances between structures increases the risk of fires spreading across multiple structures (Maranghides and Johnsson, 2008).³⁹ Several post-fire surveys have supported this conclusion. Syphard, Brennan,

³⁹ Structure-to-structure ignition has been recognized for millennia as a driver of urban conflagrations. In the United States, for example, urban conflagrations in several U.S. cities in the late 1800s led to the emergence of the first model building code, the National Building Code (Spence, Wells, and Boring, 1981, pp. 4–5). Cohen (1999) recognized that the same hazard may exist in the WUI since a highly ignitable home is a “potential participant in the continuation of wildland fire” (p. 194).

and Keeley (2014) used regression analysis to show that low density and less distance to major roads were the most important variables for explaining survivability of structures in fires in San Diego County between 2001 and 2010. Survey results of the 2012 Waldo Canyon Fire near and in Colorado Springs showed that fires can ignite rapidly in high density neighborhoods; this impedes firefighting and further reduces survivability (Maranghides, et al., 2015). These studies were further validated when the Camp Fire was observed as spreading from structure to structure (Curwen and Serna, 2018).

However, low density can also be associated with risks. Syphard et al. (2012) found that homes in less dense, fire-prone areas of San Diego County and the Santa Monica Mountains were at greatest risk. Although these homes were not exposed to nearby structures, Syphard et al. (2012, pp. 4–5) note that “scattered, isolated structures are more difficult for firefighters to defend, and poor firefighter access may explain why housing clusters with fewer roads were more vulnerable in San Diego County.”

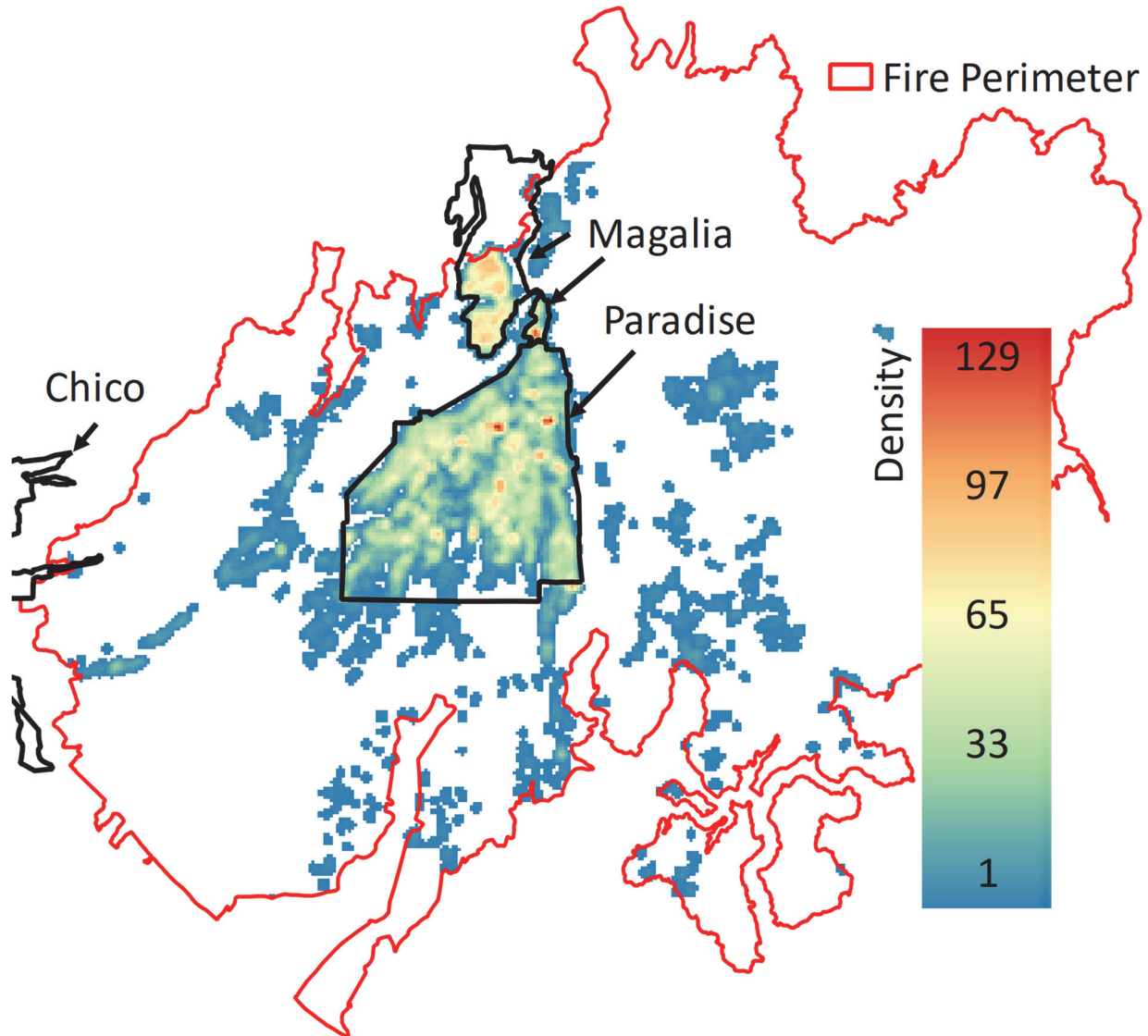
Figure 6.6 maps the density of single-family housing based on the number of single-family structures within 250 m of each point on the map, while Figure 6.7 maps the percentage of single-family homes within each 250 m radius pixel that was damaged. Higher density areas clearly experienced greater rates of damage in the Camp Fire. We hypothesize that firefighting capacity may be less relevant for the Camp Fire because there was relatively little chance to fight the fire within the major population centers. Damage among homes in the less dense fringes of Paradise varied considerably, with damages being lowest among the newer homes to the south of Paradise.

Measuring the Impact of Year Built on Survivability

We developed two econometric models to estimate the impact of year built on housing survivability. These are probit models with a binary measure of damage as the dependent variable. In order to isolate the effect of year built on survivability, the models control for other, potentially confounding factors that may influence survivability, including housing density and whether the home is permanent or manufactured. In order to account for unobserved local confounding factors, such as local fire intensity, exposure to potential structure-to-structure ignition, topography, and vegetation, we used spatial models that match each house to five nearest neighboring houses to consider the level of survivability that should have been expected, all else equal, based on the performance of neighboring houses.⁴⁰ We expected houses to have

⁴⁰ We considered alternative definitions of neighbors, such as changing the number of number of neighbors or weighting neighbors based on the inverse distance so that houses with fewer than five close neighbors weight only their nearby neighbors. Those alternatives did not have a substantial impact on the model results. We explored an alternative modeling strategy that overlayed a grid on the fire damage area and compared the houses within grid cells, but we decided not to pursue the strategy because it removed meaningful comparisons of close neighbors with different outcomes that fell across cell boundaries. Another strategy suggested by a reviewer that could be pursued

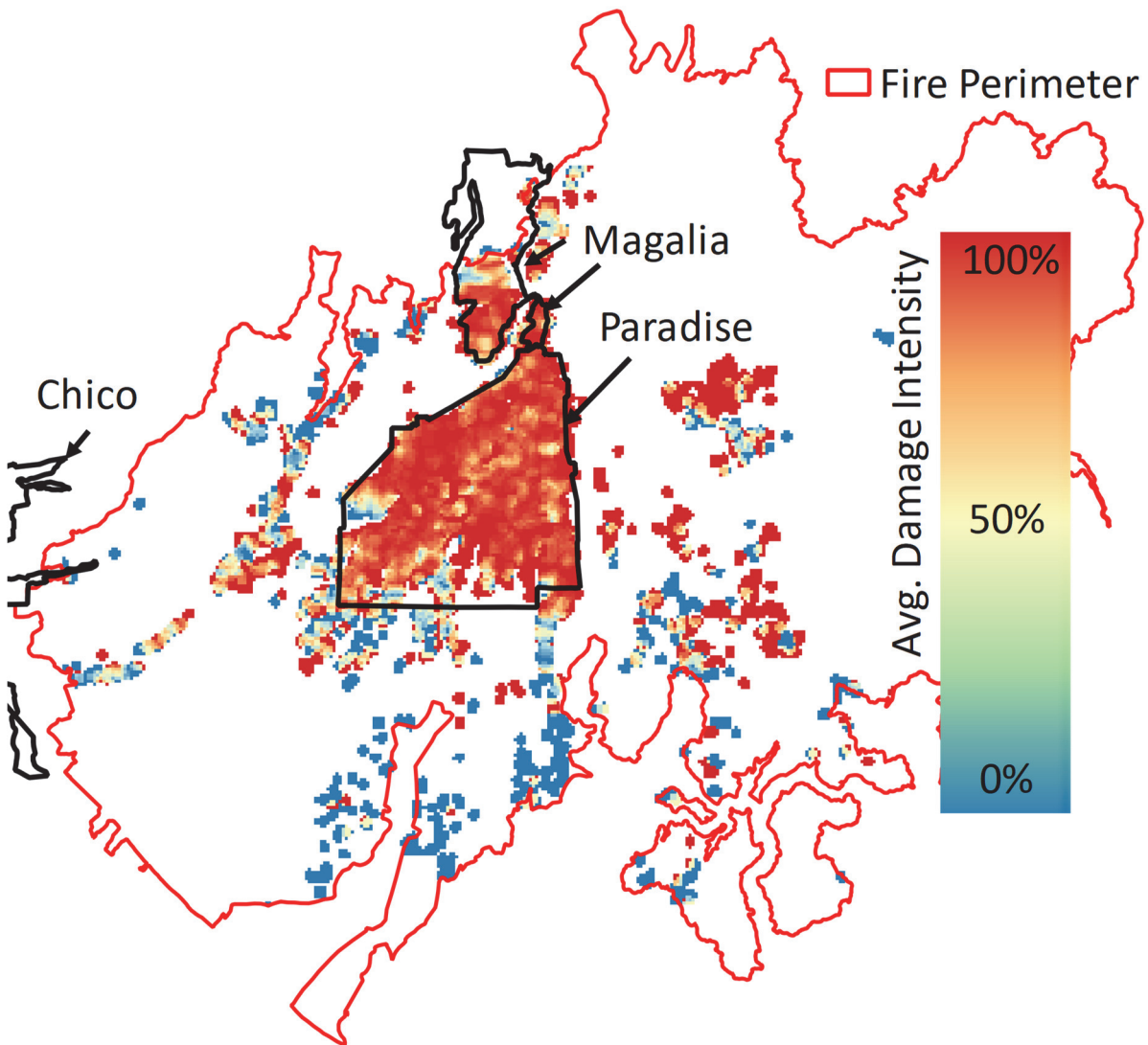
Figure 6.6. Density of Single-Family Housing



NOTES: Density is calculated as the number of single-family houses within a 250 m radius. Areas shown in white do not have any houses within 250 m.

in the future is to identify neighboring “twins” that look similar except for their year built and their survival and compare the likelihood of survivable for different decades built. We did not pursue this approach, because it would require a substantial effort to identify these twin pairs and implement a new estimation methodology, and because the results had been robust to different modeling strategies that had been more straightforward to implement. Such an approach might be especially valuable if it identified a smaller number of houses for further survey so that more detailed information about their construction features could also be included in the model.

Figure 6.7. Interpolation of Average Damage Intensity



NOTES: Damage intensity is calculated using moving average of damaged share of single-family homes within 250 m. Areas in white do not have any single-family homes within 250 m.

greater survivability when most of their neighbors survived (and vice versa) because this suggests unobserved local factors, such as fire intensity and structure-to-structure ignition, were less severe in that location. These controls allowed us to more accurately assess the relationship between the age of a home and its survivability,⁴¹ with the goal of informing whether houses

⁴¹ Figure 6.3 suggests that houses have become more survivable over time, but Figure 6.7 shows that damage of neighboring houses is strongly correlated. If new houses, for example, tend to be built in less vulnerable locations, then it may appear that houses are becoming more survivable over time even though the real driver is that houses are being built in less vulnerable locations. These econometric models control for these factors to better estimate the true, unbiased relationship between age of houses and their survivability.

built under more recent standards and building practices were more likely to survive the Camp Fire wildfire.

Two Approaches

We used two different approaches to measure the relationship between the age of the house and its survivability. Both approaches included the outcomes of neighboring houses as a control to account for unobserved local confounding factors, but the two models differ in how they determine the risk neighboring houses impose in hypothetical counterfactuals. We refer to these two approaches as a “static” model and a “recursive” model. We present both approaches because neither is inherently superior to the other.

The static model treats the unobserved local risks proxied by neighboring houses’ damage as fixed across hypothetical counterfactuals. Both models use the decade in which a house was built as one predictor of its survivability. In the static model, if we estimate how survivability would change if all houses were built in 2000, we still assume all other factors, including the extent to which neighboring houses are damaged, remain unchanged.

The recursive model acknowledges that these unobserved local risks, particularly structure-to-structure ignition, may change in hypothetical counterfactuals. In the recursive model, if we estimate how survivability would change if all houses were built in 2000, we account for the fact that if a house being built in the 2000 instead of the 1960s reduces its chances of being destroyed, that would also reduce the chances its neighbors will be destroyed. This impact propagates to some extent by reducing the probability of damage to its neighbors’ neighbors, and so on. Structural improvements across houses thereby see a magnified effect in the recursive model because the improvements reduce the likelihood of damage to a house while also reducing the likelihood of damage to a house’s neighbors.

This difference in the treatment of risk from neighboring homes is the only difference between the two models; all other independent variables are the same. We do not view one approach as inherently superior to the other, as which estimate is most appropriate depends on the extent to which the key unobserved local factors are mainly constant across counterfactuals (such as topography and geography) or items that would change in counterfactuals (such as structure-to-structure ignition).

In the static model, the damage to the five nearest neighbors are weighted equally, so each house’s spatial lag variable has a value of 0, 0.2, 0.4, 0.6, 0.8, or 1 depending on whether 0, 1, 2, 3, 4, or 5 of its neighbors are damaged, respectively. The main benefits of this approach is that it is much simpler to understand, interpret, and implement. The main drawback is that it does not account for changes in risk from neighboring households in our hypothetical analysis of expected damages when all houses are built in a particular decade—that is, the value of 0, 0.2, 0.4, 0.6, 0.8, or 1 remains unchanged.

In the recursive model, the average damage to neighboring homes is based on the predicted probability of damage, rather than a binary indicator of whether damage occurred in practice.

Because the predicted probability of damage for one observation is dependent on the predicted probability of damage for another observation, the probit must be calculated using a simultaneous equations approach, which essentially iterates over possible coefficient values until it converges on a stable solution. The main benefit of this approach is that it accounts for changes in risk from neighboring households in our hypothetical analysis of expected damages when all houses are built in a particular decade.

In other words, the recursive model accounts for a house imposing less risk on its neighbors if it was built in a more recent year (if houses built in more recent years are at lower risk of damage). However, the main downside of this approach is that it may incorporate impacts beyond the impact of building a home to updated standards; it could also reflect differences in risk to newer homes due to geography, fire intensity, or other variables that are independent of home construction and would not be changed in practice if all houses were retroactively updated to more recent codes. As a result, the recursive model could exaggerate the extent to which the probability of damage to neighboring homes could be reduced.

Table 6.2 presents summary statistics of the variables included in this analysis. We note that damaged houses have about twice as many damaged neighbors (93 percent) than undamaged houses (47 percent). This highlights the importance of considering damage to neighbors when predicting whether a house is damaged. Further econometric details associated with this analysis are discussed in Appendix C.

Table 6.2. Summary Statistics for Damaged and Undamaged Houses in the 2018 Camp Fire

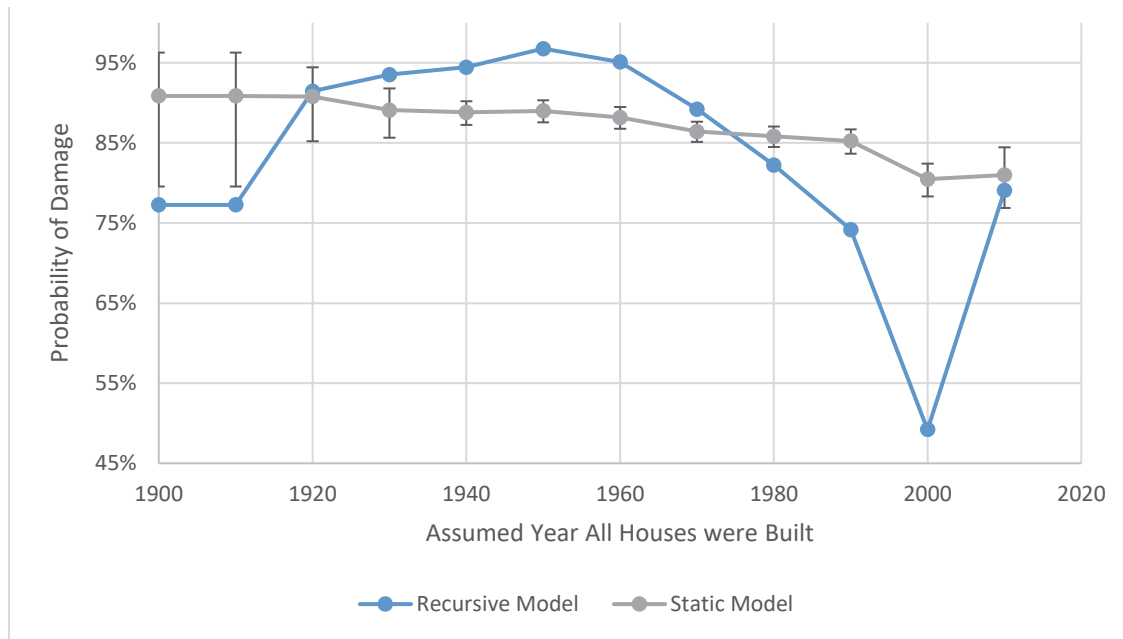
	Undamaged		Damaged		All	
	Count	% of Row	Count	% of Row	Count	% of Total
All houses	2,153	14%	13,333	86%	15,486	100%
Permanent houses	1,928	16%	10,100	84%	12,028	78%
Manufactured houses	225	7%	3,233	93%	3,458	22%
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Year built	1983.8	18.89	1972.0	17.73	1973.6	18.36
Density (100 m)	4.69	4.48	8.6	5.99	8.06	5.96
Density (1 km)	327.29	289.10	518.36	211.71	491.79	233.62
Average share of neighbors damaged	47%	0.35	93%	0.16	86%	0.35

NOTE: Density reflects the number of neighboring houses within a 100 m or 1 km radius.

Model Results

Figure 6.8 shows the predicted probability of damage, assuming all houses were built in the same decade. For example, if all houses were built in the 1950s, the recursive model predicts that they would average a 97-percent chance of damage, while the static model predicts they would average an 89-percent chance of damage.

Figure 6.8. Predicted Probability of Damage If All Houses Were Built in a Given Decade



NOTES: Ninety-five-percent confidence intervals are in brackets for the static model. We were not able to calculate confidence intervals for the recursive model.

Both the recursive and static model show increasing levels of survivability between the 1950s and 2000s, then a reduction in survivability in the 2010s. As shown in Figure 6.1, there are fewer houses on which to base estimates prior to 1940 and after 2010. The standard errors on the static model are especially large during those years for this reason, and we similarly have less confidence in the precision of point estimates of the recursive model prior to 1940 and for 2010.⁴² As described previously, differences between these estimates are driven by differences in the role of accounting for feedback loops between neighboring houses, although the differences might also include the effect of other geographically correlated features (such as geography, fire intensity, or other spatially correlated variables) being similar to what was experienced by households built in that decade. Thus, while the static model might not fully account for the benefits of reduced structure-to-structure ignition, we cannot say with confidence whether the difference between the recursive and static model over- or under-estimates the impact of structure-to-structure ignition.

We find no evidence to support the hypothesis that the 2008 implementation of the WUI building code in Chapter 7A led to a discrete increase in housing survivability. Both models

⁴² We were not able to calculate standard errors for the recursive model due to its complexity, although we expect the true standard errors are larger in 2000 (which has a larger standard error in the static model than in previous decades), 2010, and prior to 1940 and that the recursive model's standard errors are likely to be larger than those of the static model due to its feedback effects.

predict houses built in the 2000s to be the most survivable, but most years in that decade were not subject to the requirements of Chapter 7A.⁴³

Given the lack of evidence regarding the impact of Chapter 7A, there are other explanations of why survivability of housing has been increasing in newer homes (at least until the 2010s) other than changes in building construction driven by WUI building codes and laws. We hypothesize that other drivers or factors associated with both building age and survivability could also explain this result. These include

- **Changes to other codes or building practices:** Building codes are regularly updated. In 2005 the defensible space law was amended to increase the required defensible space from 30 ft. to 100 ft.⁴⁴ Codes with other primary purposes may also reduce fire risks. For example, energy efficiency requirements around double-paned windows can increase wildfire survivability. Housing styles and best practice for construction (beyond those required by codes) may change over time in ways that may be correlated with fire risk. For example, a Headwaters Economics/IBHS report on building wildfire-resistant homes recommended installing weed- and erosion-control fabric within 5 ft. of houses to prevent growth (Quarles and Pohl, 2018). In addition, newer homes may be developed on larger lots, which could increase stand-off distances and decrease housing density.
- **Changes in code compliance:** Changes in codes do not necessarily lead to changes to building design if the codes are not adopted by municipalities or builders and homeowners do not abide by the code requirements. There is some evidence that compliance has been increasing in California between 2005 and 2015, which may have contributed in part to improved survivability among homes built in the 2000s and 2010s.⁴⁵
- **Difference in maintenance of homes:** Older homes may be more likely to have deferred maintenance risks, such as encroachment of vegetation into a house's defensible space, relative to newer homes.

Damage to neighboring households is a major driver of risk in both models. Although we cannot set hypothetical values of damage to neighboring households in the recursive model, the static model predicts the average house with no damaged neighbors has a 14-percent chance of damage versus a 96-percent chance of damage if all its neighbors are damaged. This result is consistent with structure-to-structure ignition being a major mechanism by which houses in the

⁴³ We explored a variety of alternative model formulations with different cutoffs in years and did not see evidence that houses built after 2005 (when the first provisions of Chapter 7A were implemented) or built after 2008 showed any sudden increases in survivability. However, many of the models pointed to the late 1990s to early 2000s as a time when there may have been a sudden increase.

⁴⁴ See CAL FIRE (undated b).

⁴⁵ Insurance Services Office, Inc., grades building code adoption and enforcement in communities through its Building Code Effectiveness Grading Schedule (BCEGS), which grades on a scale of 1 (best) to 10 (worst) using criteria such as the currency of codes and the qualifications of enforcement employees (Dwyer, 2012). Average grades improved nationally between 2005 and 2015 for residences from 5.6 to 5.2 and improved in California from 6 to 3 (Insurance Services Office, Inc., undated). As of October 2019, the Town of Paradise had a BCEGS score of 3 (Butte County, 2019, p. E-62). We were unable to assess trends in the scores—as of May 2013 the BCEGS score of Town of Paradise had not been assessed (Butte County, 2013, p. E.36).

Camp Fire ignited; this is similar to other observations such as those by NIST researchers in the Waldo Canyon Fire (Maranghides et al., 2015). However, this strong correlation between neighboring houses’ outcomes could also reflect neighboring houses sharing other high-risk characteristics. Collecting and analyzing additional data about structure features, land use, and fire behavior—for both damaged and undamaged homes and areas—would support further investigation of this issue.

The Value of Potential Damage Reduction

Given the current difficulties in establishing whether changes in WUI standards and codes have led to changes to WUI building design and whether those design changes have led to increased survivability of buildings to wildland fires (see Figure 6.1), it would be premature to attempt to measure the economic impacts of WUI building codes and standards. Therefore, in this section we present a simple estimate of the difference between the actual property loss from the Camp Fire and a hypothetical property loss that would have resulted if all houses had been built in the 2000s (i.e., the decade with the lowest predicted level of damage). We refer to this hypothetical property loss as the *adjusted loss*. This difference is intended to represent an estimate of the cumulative economic impact of advancements in wildfire survivability resulting from standards, codes, and other influences over the past ~ 100 years.

Our assessment is limited to property loss damages that would be potentially averted, per the results of our earlier analysis. We acknowledge that there are many potential direct impacts to humans (i.e., deaths and injuries) and the natural and built environment (e.g., cleanup costs of the Camp Fire were estimated at \$3 billion [Elias, 2018]), but the damages to structures appear to be the most prominent type of direct impact that would benefit from changes to building codes.

We estimate the potential economic benefits of these changes according to the following equation:

$$\text{Damage Averted (\$)} = \text{Actual Loss (\$)} - \text{Adjusted Loss (\$)},$$

where

$$\text{Adjusted Loss (\$)} = \text{Estimated \% of Homes Damaged} \times \frac{\text{Actual Loss(\$)}}{\text{Actual \% of Homes Damaged}}.$$

For “Actual Losses (\$),” we use the \$9.3 billion estimate from CoreLogic (Jeffery et al., 2019), which uses a database of residential properties to estimate the reconstruction cost value of damages.⁴⁶ CoreLogic’s value is based on 18,804 destroyed residential structures. This is larger than the 13,108 damaged or destroyed single family homes to which we restrict our analysis; for

⁴⁶ Munich RE estimated total damages of the Camp Fire to be \$16.5 billion (Löw, 2019). However, this figure is not limited to damage in residential properties.

simplicity this calculation assumes the percentage of these other residential structures that were damaged (or would be damaged in our hypothetical estimate) is similar to that of the single-family homes examined in our analysis.

Table 6.3 shows that, under these assumptions, the static model estimates the damage averted to be \$600 million if all houses had the same survivability as those built in the 2000s, while the recursive model estimates the damage averted to be \$4 billion if all houses had the same survivability as houses built in the 2000s. We note that the \$600 million estimate may be low because it does not fully account for the benefits of reduced structure-to-structure ignition. However, we acknowledge that the \$4 billion estimate may be biased in unknown directions because it may extrapolate benefits beyond housing construction (such as geographic characteristics and the average fire intensity to which houses built in the 2000s were exposed) to all houses.

Table 6.3. Estimates of Camp Fire Damage Averted If All Residential Structure Were as Survivable as Single-Family Houses Built in the 2000s

	Recursive	Static
Actual loss (\$)	\$9.3 billion	\$9.3 billion
Actual % of homes damaged	86%	86%
Estimated % of homes damaged	49.2%	80.5%
Adjusted loss (\$)	\$5.3 billion	\$8.7 billion
Damage averted (\$)	\$4.0 billion	\$0.6 billion

With richer data, similar calculations could be performed to understand the potential damage averted from specific building features. For example, if undamaged houses had vent mesh data, then the models could include vent mesh as an explanatory variable and predict changes in damage likelihood if all houses were retrofitted with improved vent mesh, which could be valued according to the equation above.

Conclusion

WUI standards and codes, and the research underlying them, are nascent in comparison with the standards, codes, and research involving smoke alarms. As WUI science matures, new standards and codes will be developed and their economic impacts will become clearer. Improvements in data collection could support this process, particularly data collection on undamaged homes and on compliance with existing WUI standards. Current data rarely assess whether damaged structures complied with code requirements, which challenges assessments of the efficacy of code requirements. Similarly, a lack of data on the characteristics of undamaged structures makes it difficult to identify factors associated with improved survivability. NIST has been encouraging improvements in data collection, and some efforts are already underway.

Using the 2018 Camp Fire as a case study, this chapter has found evidence that houses have generally become more survivable over time, although data limitations prevent precise measurement of the relative survivability of the very oldest and the most recent homes. These results are consistent with a hypothesis that improvements to building codes over time have led to (or occurred alongside) changes in building designs and materials that have improved the survivability of houses to fire. However, our results do not find a statistically significant increase in survivability following the WUI-specific building codes first enforced in 2005.

We used two different approaches to estimate the potentially averted damage if all houses were as survivable as houses built in 2000 to 2009 (the decade when houses built had the lowest damage rates). Our static approach estimates this increased survivability would have resulted in a 6-percent reduction in the number of damaged houses (from 86 percent to 80.5 percent), with associated economic value of approximately \$600 million. However, this method likely underestimates the benefits of reduced structure-to-structure ignition. Our recursive approach, which is designed to account for structure-to-structure ignition, estimates this increased survivability would have resulted in a 43-percent reduction in the number of damaged houses (from 86 percent to 49.2 percent), with associated economic value of approximately \$4 billion. However, this method may over- or underestimate the extent to which neighboring structures can reduce their ignition risk through changes in construction practices.

Although the Camp Fire is a historic outlier in its severity, the value of potential reduction in damages if all houses were as survivable as newer houses—worth at least hundreds of millions, if not billions of dollars for a single WUI fire, by our estimates—along with the potential for future severe WUI fires, appears to clearly justify a robust research effort to understand how to improve structure survivability to fires.

7. Conclusion

A large number of steps and organizations are involved in the process of developing new fire safety standards, as with new standards in general. NIST's principal role comes at the very beginning of this process—providing the foundational research on which subsequent activities are built. NIST research helps SDOs develop consensus around potential standards, which are often incorporated into public building codes and, in turn, save lives by improving fire safety.

In addition, NIST researchers and staff proactively engage with stakeholders to ensure that NIST's findings and other research results are being transitioned and incorporated into the standards and codes development process. NIST researchers and staff actively participate in SDOs, often serving as committee chairs or in other leadership positions. In these roles, they help inform other committee members, evaluate and update existing standards, and propose new standards. We found that there is a clear sense of respect and gratitude among SDO representatives for NIST's role in standard development activities

NIST research is also instrumental in the development and design of standardized tests that are used to systematically evaluate technologies and to confirm compliance with standards. Indeed, the need for nationally standardized methods, processes, and measures was what led to the creation of the organization. As new products and safety challenges continue to arise, the need for such services continues.

NIST's key contributions described in this report include

- continuous research on fire safety since 1914
- continuous membership and active participation on technical committees for several SDOs addressing fire safety standards, including NFPA, ASTM, UL, ICC, ISO, and others
- leveraging early research to begin advocating for including smoke alarms in homes and to launch studies of smoke alarm design, performance, and use, which led to the first smoke alarm standard
- continuing to provide valuable research on smoke alarm performance, testing, and siting, with particular attention to evolving home furnishing materials and nuisance alarms
- Contributing, through its cumulative body of work, to 95 percent of U.S. homes having a working smoke alarm
- helping demonstrate the importance of firebrands in igniting structures in wildland fires
- conducting detailed analyses of fires to assess modes of fire spread and structure damage mechanisms and to identify protective measures and their effectiveness
- developing standardized testing equipment and methods that help objectively examine impacts of wildfire safety measures.

Our analysis identified a number of important contributions from NIST toward the development and adoption of standards for smoke alarms and WUI protection. While our quantitative analyses were not able to detect significant economic benefits that can be linked

directly to these standards, this in no way suggests that the standards, and NIST's contributions to them, do not have great value. In the case of smoke alarms, the most important gains were likely made prior to the time period for which we conducted our analysis. Conversely, in the WUI setting, standards are still in the active research stages, and the biggest benefits are likely yet to be realized. More generally, standards are likely to have indirect economic benefits, such as increasing technology development and adoption and efficiency of markets, which our analyses cannot capture.

Many organizations, including NIST, are involved in supporting the development and implementation of fire safety standards. The results of their collaborative activities are not easily traced to individual contributors. However, it is clear that NIST's role is critical and that substitutes for NIST are not readily apparent. NIST's accomplishments and historical continuity in fire safety research, its mission- and needs-driven approach to selecting research topics, and its credibility for conducting objective, high quality research make it a crucial contributor in the development of fire safety standards. If NIST were to become unable to perform its research activities, long-term progress on fire safety standards would be substantially affected.

Appendix A. National Institute of Standards and Technology Fire Research Division Survey

In September 2019, we conducted a survey of NIST Fire Research Division research staff to help us understand their involvement in standards development. The questions asked included the level and duration of involvement with SDOs and with particular smoke alarm and WUI standards. The division research staff were contacted via email by the Division Chief, who provided a brief description of the study and a link to the survey instrument. The survey was sent out to all 42 scientific researchers in the Fire Research Division, which included 27 full-time staff, 3 part-time staff, 3 contract researchers, 6 foreign guest researchers, and 3 postdoctoral associates. We received 29 completed survey responses from these current NIST researchers, as well as one response from an emeritus researcher.⁴⁷

The survey instrument is reproduced below. We deliberately kept the instrument very brief; we estimate that it took no more than five minutes to complete.

⁴⁷ Our presented results do not currently include the emeritus researcher in order to reflect the activities of current NIST staff at the time of the survey. However, the emeritus researcher, who was deeply involved in both NIST and SDOs, suggests that this survey does not reflect an unusual level of engagement with SDOs but rather a steady focus on engagement with SDOs.

The Role of NIST Fire Safety Research in Standards Development

About This Survey

Through its Technology Partnerships Office, NIST has asked the RAND Corporation (www.rand.org) to evaluate NIST's contribution towards the development of standards in two specific areas: smoke alarms and wildland-urban interface (WUI) fire protection. As part of that effort, we are reaching out to researchers in the Fire Research Division to understand their interactions with standards development organizations (SDOs). This information will help inform the second part of the study, which will estimate the economic impact of these standards.

We would very much appreciate you completing this brief survey, which is expected to take no more than 5 minutes to complete. Please click the "Done" button at the bottom of the page to submit your response. Responses will kept anonymous and presented in aggregated form only. If you have any questions or concerns, please contact Nelson Bryner, Chief of the NIST Fire Research Division (nelson.bryner@nist.gov) or Ben Miller, co-project leader at RAND (bmiller@rand.org). Thanks in advance for taking a few moments to help us with this important work.

1. Have you ever been involved with any of the following standards development organizations? Please check all that apply. If none, please check any column in the "I have not been involved with any standards development organizations" row and skip the remaining questions. Please still click the "Done" button below to submit your survey response.

	Non-Voting Member	Voting Member	Committee or Subcommittee Chair	Other
ASTM International	☐	☐	☐	☐
International Code Council (ICC)	☐	☐	☐	☐
International Organization for Standardization (ISO)	☐	☐	☐	☐
National Electrical Manufacturers Association (NEMA)	☐	☐	☐	☐
National Fire Protection Association (NFPA)	☐	☐	☐	☐
Underwriters Laboratories (UL)	☐	☐	☐	☐
Other	☐	☐	☐	☐

I have not been involved with any standards development organizations ☐ ☐ ☐ ☐

2. Have you been involved with any of the following standards?

- ☐ ASTM E2707-15: Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure
- ☐ ASTM E2957-17: Standard Test Method for Resistance to Wildfire Penetration of Eaves, Soffits and Other Projections
- ☐ ASTM WK23700: New Test Method for Evaluating Roof Field Vent Response to Wind Blown Flame and Burning Ember Exposure
- ☐ ASTM D2898: Standard Practice for Accelerated Weathering of Fire-Retardant-Treated Wood for Fire Testing
- ☐ ASTM D3909/D3909M: Standard Specification for Asphalt Roll Roofing (Glass Felt) Surfaced With Mineral Granules
- ☐ ASTM D6662: Standard Specification for Polyolefin-Based Plastic Lumber Decking Boards
- ☐ ASTM D7032: Standard Specification for Establishing Performance Ratings for Wood-Plastic Composite and Plastic Lumber Deck Boards, Stair Treads, Guards, and Handrails
- ☐ ASTM E84: Standard Test Method for Surface Burning Characteristics of Building Materials
- ☐ ASTM E108: Standard Test Methods for Fire Tests of Roof Coverings
- ☐ ASTM E119: Standard Test Methods for Fire Tests of Building Construction and Materials
- ☐ ASTM E136: Standard Test Method for Assessing Combustibility of Materials Using a Vertical Tube Furnace at 750°C
- ☐ ASTM E2652: Standard Test Method for Assessing Combustibility of Materials Using a Tube Furnace with a Cone-shaped Airflow Stabilizer, at 750°C
- ☐ ASTM E2768: Standard Test Method for Extended Duration Surface Burning Characteristics of Building Materials (30 min Tunnel Test)
- ☐ ASTM E2886: Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement
- ☐ ICC International Building Code/International Fire Code
- ☐ ICC Wildland Urban Interface Code
- ☐ ISO 12239: Fire Detection and Fire Alarm Systems - Smoke Alarms (2003); Smoke Alarms Using Scattered Light, Transmitted Light or Ionization (2010)
- ☐ NEMA SB-11: Guide for Proper Use of System Smoke Detectors
- ☐ NFPA 72: National Fire Alarm and Signaling Code
- ☐ NFPA 101: Life Safety Code
- ☐ NFPA 1141: Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas
- ☐ NFPA 1143: Standard for Wildland Fire Management
- ☐ NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire
- ☐ NFPA 5000: Building Construction and Safety Code
- ☐ UL 217: Standard for Smoke Alarms
- ☐ UL 268: Smoke Detectors for Fire Alarm Systems
- ☐ UL 273: Standard for Test for Surface Burning Characteristics of Building Materials
- ☐ UL 790: Standard for Standard Test Methods for Fire Tests of Roof Coverings
- ☐ Other, please specify:

3. Which most closely describes the amount of time you spend on activities with or for standards development organizations?
- ☐ Only trivial amounts of time
 - ☐ I typically attend one meeting per year OR spend a few days per year supporting SDO activities
 - ☐ I attend meetings and spend a few days per year supporting SDO activities
 - ☐ I attend meetings and spend a few days per month supporting SDO activities
 - ☐ I spend more time than any of the above options on SDO activities
4. What is your total length of service for all of the activities listed above?
- ☐ < 1 year
 - ☐ 1–3 years
 - ☐ 3–5 years
 - ☐ > 5 years
5. Have you ever submitted a formal proposal, revision, or comments for this SDO?
- ☐ ASTM International
 - ☐ International Code Council (ICC)
 - ☐ International Organization for Standardization (ISO)
 - ☐ National Electrical Manufacturers Association (NEMA)
 - ☐ National Fire Protection Association (NFPA)
 - ☐ Underwriters Laboratories (UL)
 - ☐ Other, please specify
-
6. Have you ever engaged with SDO activities or deliberations in other ways (e.g., given a presentation at an SDO event, communicated with SDO members about standards, etc.)?

Appendix B. Statistical Methods for Assessing the Impact of Smoke Alarm Standards on Fire Outcomes

Chapter 4 of this report presents a two-step statistical analysis for examining the relationship between the proportion of houses subject to statewide minimum residential building code updates and the number of fires, injuries, or fatalities reported to NFIRS. This appendix further documents the statistical methods employed in that analysis.

Step 1: Estimating the Propensity to Report to NFIRS

A challenge in using NFIRS data for this analysis is that NFIRS is a collection of voluntary reports from individual fire departments, rather than comprehensive data from a random selection of fire departments. Consequently, outcomes in NFIRS are not necessarily representative of average outcomes. However, Butry and Thomas (2012, pg. iii) “develop a statistical approach for evaluating the ‘representativeness’ of fire incident data reported in the National Fire Incident Reporting System (NFIRS) to depict fire activity in non-reporting cities.”⁴⁸ We apply an approach that is similar in spirit, although ours is designed to ensure “representativeness” at the individual fire department level, rather than the city level as implemented by Butry and Thomas (2012).

Estimating the probability that a fire department reports to NFIRS requires information about both departments that report to NFIRS and those that do not. Two additional data sets were utilized to obtain variables that may be correlated with the decision of whether or not to participate in NFIRS: the Census of Population and Housing (U.S. Census, undated a, undated b) and the National Fire Department Registry (USFA, 2020). The Census of Population and Housing contains socioeconomic variables describing populations, such as income, sex, and race, as well as housing items such as the status of housing units (occupied or unoccupied), the median age of housing units, and the median value of housing units. We match fire departments to the demographic data of the zip code of their department headquarters.⁴⁹

The National Fire Department Registry contains basic information about fire departments listed with the U.S. Fire Administration (USFA). We use this data to identify departments that do not report to NFIRS and to understand information about all fire departments. Unfortunately, there is not a single official list of all fire departments in the United States, or even a definitive count of how many exist. Evarts and Sein (2020) states that there are 29,705 fire departments,

⁴⁸ We are grateful to Butry and Thomas for sharing their code and insights with us.

⁴⁹ For departments for which we do not know the headquarter’s zip code, we use the zip code most commonly listed in the incident address of NFIRS reports provided by that department.

based on the NFPA Fire Service Survey, 2016–2018, and NFPA Survey of Fire Departments for US Fire Experience, 2018 (Evarts and Stein, 2020). USFA (2020) cites an NFPA estimate of 29,819 fire departments in the United States as of 2017, of which 27,200 are in the USFA registry.

As of August, 2020, we found 27,176 fire departments in the USFA registry. Most of these can be matched to fire departments in the NFIRS database via the commonly used “Fire Department ID” (FDID). However, we found 3,503 FDIDs in NFIRS that did not match to the USFA registry, and 221 fire departments in the USFA registry that did not have FDIDs.⁵⁰ Based on this information, we believe that there are approximately 30,000 fire departments in the United States. Reporting rates vary by year, with more departments reporting to NFIRS in more recent years. For example, we were able to match 90 percent of the 2017 NFIRS records to a department, and 75 percent of departments to at least one NFIRS record. Of the departments that we can match to NFIRS records, we are able to identify or estimate a headquarters zip code for almost all departments (more than 99 percent). We were then able to match almost all of these zip codes to 2018 American Community Survey (ACS) data (99.78-percent success rate for the 2017 NFIRS-USFA data).

Information from the Census of Population and Housing and the National Fire Department Registry shows that primary departments from wealthier and more urban areas that are staffed with career firefighters are more likely to report to NFIRS than relatively rural, volunteer-based departments (Table B.1). For this reason, adjustments are required to ensure the NFIRS data reflect nationally representative outcomes. Like Butry and Thomas (2012), we make these adjustments by calculating propensity scores that account for the probability that a given department would report to NFIRS, based on observable characteristics of that department. We then use this propensity score to place more weight on observations from departments that are relatively less likely to report to NFIRS.

We use a probit model to estimate a propensity score that reflects each fire department’s probability of reporting to NFIRS.⁵¹ We perform the propensity score estimation separately for each year of our data because the number of departments reporting to NFIRS has increased over time. This propensity score is calculated based on characteristics of the zip code tabulation area of the fire department’s headquarters in 2018 and on characteristics of the fire department itself. Characteristics of the zip code tabulation area including the total population; the number of residential housing units; the proportion of the population that lives in urban areas; the mean per-person income; the proportion of the population living below the poverty threshold; the percentage of the population that is white; and the proportion of residential housing units that are

⁵⁰ We assume departments without listed FDIDs did not report to NFIRS, as an FDID is a required field item for reporting to NFIRS.

⁵¹ Specifically, we use the probit model within Stata’s `-t effects ps match-` algorithm for propensity score matching, which produces propensity scores.

Table B.1. Selection Bias in Reporting to the National Fire Incident Report System, 2017 Data

Variable		Mean Value, Departments That Report to NFIRS	Mean Value, Departments That Do Not Report to NFIRS	F-Statistic for Difference
HQ Zip Code	Population	12,626	9,338	301.9
	Per capita income	\$74,796	\$68,784	245.5
	Percentage urban	43%	31%	523.7
	Percentage white	86%	85%	22.2
	Number of residential units	5,492	4,066	342.5
	Percentage owner-occupied	62%	58%	271.9
	Percentage vacant	16%	20%	398.4
Department	Percentage that are a local department	98%	92%	480.1
	Percentage that are the primary agency	33%	17%	663.7
	Percentage that are a purely volunteer department	67%	79%	387.5
	Number of career firefighters	15.34	7.28	32.3
	Number of volunteer firefighters	22.25	20.61	10.8

SOURCE: RAND analysis of data from NFIRS, the National Fire Department Registry, and ACS. This table reflects 2017 reports to NFIRS and 2018 ACS data.

vacant. Characteristics of the fire department include indicators for whether the department is staffed with only career firefighters, mostly career firefighters, mostly volunteer firefighters, or only volunteer firefighters; the total number of firefighters in the department; the number of fire stations in the department; indicators for whether the department is a local or nonlocal organization; and an indicator for whether the department is the primary agency for emergency management.⁵² These variables are drawn from two additional data sets: the Census of Population and Housing (U.S. Census, undated a, undated b) and the National Fire Department Registry (USFA, 2020).

We use the resulting propensity scores to place more weight on reports from fire departments that were less likely to report to NFIRS, which helps ensure the results of our second-stage analysis are representative rather than reflecting bias in the type of departments that report to NFIRS.⁵³

⁵² These variables were selected by taking our full list of candidate variables from the Census of Population and Housing and the National Fire Department Registry and (1) excluding those that are not statistically different between reporters and nonreporters, and (2) identifying highly correlated confounding variables and excluding either the one with fewer observations or the one with a large p -value/lower F -statistic. Then, because the model would not converge if the number of active career and volunteer firefighters were measured separately, we exclude those two variables and instead include their sum, which is the total number of active firefighters.

⁵³ Our results are representative based on the observables included in our propensity score analysis. We cannot correct for biases in which fire departments' reports to NFIRS are uncorrelated with any observed data.

Step 2: Estimating the Relationship Between Fire Outcomes and the Proportion of Houses Built Since Code Enactment

Once we have determined the proportion of houses built since a code was enacted and how much weight to put on reports from different fire departments, the remainder of our analysis is fairly straightforward.

First, we aggregate the number of fires of different severities, as well as the number of injuries and fatalities, from the department level to the state level. The propensity scores calculated in Step 1 of our analysis are used to construct the probability weights used in this aggregation.⁵⁴ Because states vary considerably in population, we calculate a more comparable “per capita” style measure of the number of fires per 100,000 houses for each state and year.

We then estimate the correlation between the number of fires per 100,000 houses in a state and the proportion of that state’s houses that were built following the enactment of a specific edition of NFPA 72 into the state code. A separate Poisson regression is run for each possible combination of fire severity and NFPA edition. The results are presented in Table 4.3 as a matrix of five different severities of fire (from the most severe fires which spread beyond the building of origin, to the least severe fires which are confined to the object of origin) and four different editions of NFPA 72 (the 1999, 2002, 2007, and 2010 editions).⁵⁵ All regressions include both year and state fixed effects, meaning the results presented in Table 4.3 reflect the correlation after accounting for year-specific and state-specific factors (e.g., a particular year or state having an unusually large number of high-severity fires). Our main results exclude a small number of outliers,⁵⁶ although results based on all observations are comparable.

Outliers

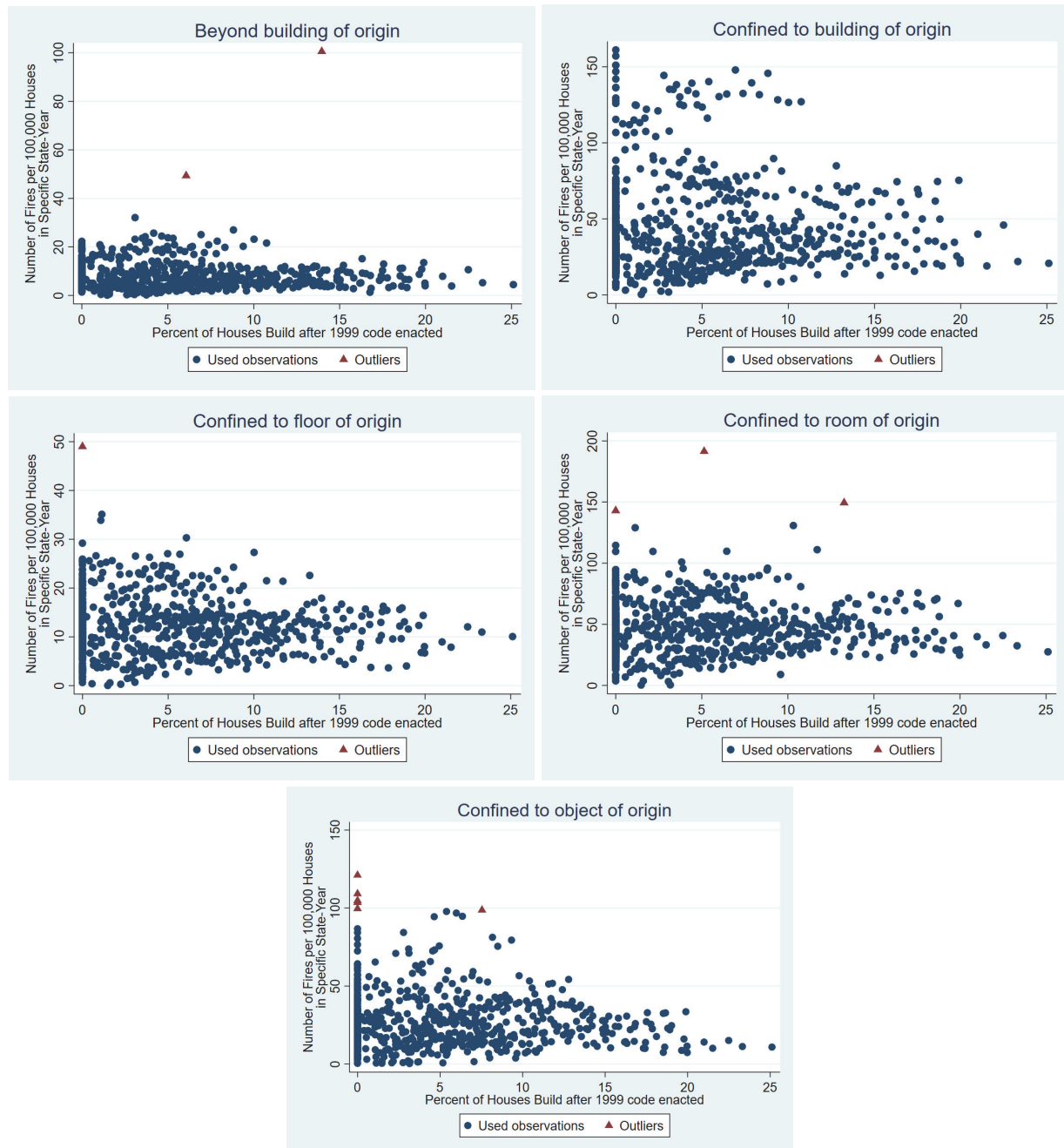
There are several outliers in the data used in this analysis that ex ante appear unrelated to the mechanism of interest (the adoption of standards) and could possibly bias results (although this analysis shows they do not). First, Figure B.1 shows the number of fires of different severities per 100,000 homes (the dependent variable) relative to the proportion of homes built since the 1999 code was enacted (one of the independent variables of interest; the choice of the 1999 code

⁵⁴ Specifically, we use Stata’s -collapse- function to aggregate the data from the department-year level to the state-year level, using the inverse of the propensity score calculated in Step 1 (1/propensity score) as a probability weight.

⁵⁵ Sufficient data are not available to examine later editions.

⁵⁶ We exclude observations where the residual number of fires of a given severity per 100,000 homes is more than 4 standard deviations above or below the mean after accounting for state and year fixed effects. In some cases, these large outliers are associated with major wildfire outbreaks, and the impacts of wildfires are unlikely to reflect on the effectiveness or ineffectiveness of smoke alarm codes. However, Appendix C shows that the inclusion or exclusion of these observations does not meaningfully change the results. See Chapter 4 for our separate analysis of the potential impact of WUI standards.

Figure B.1. Outliers in the Number of Fires per Capita

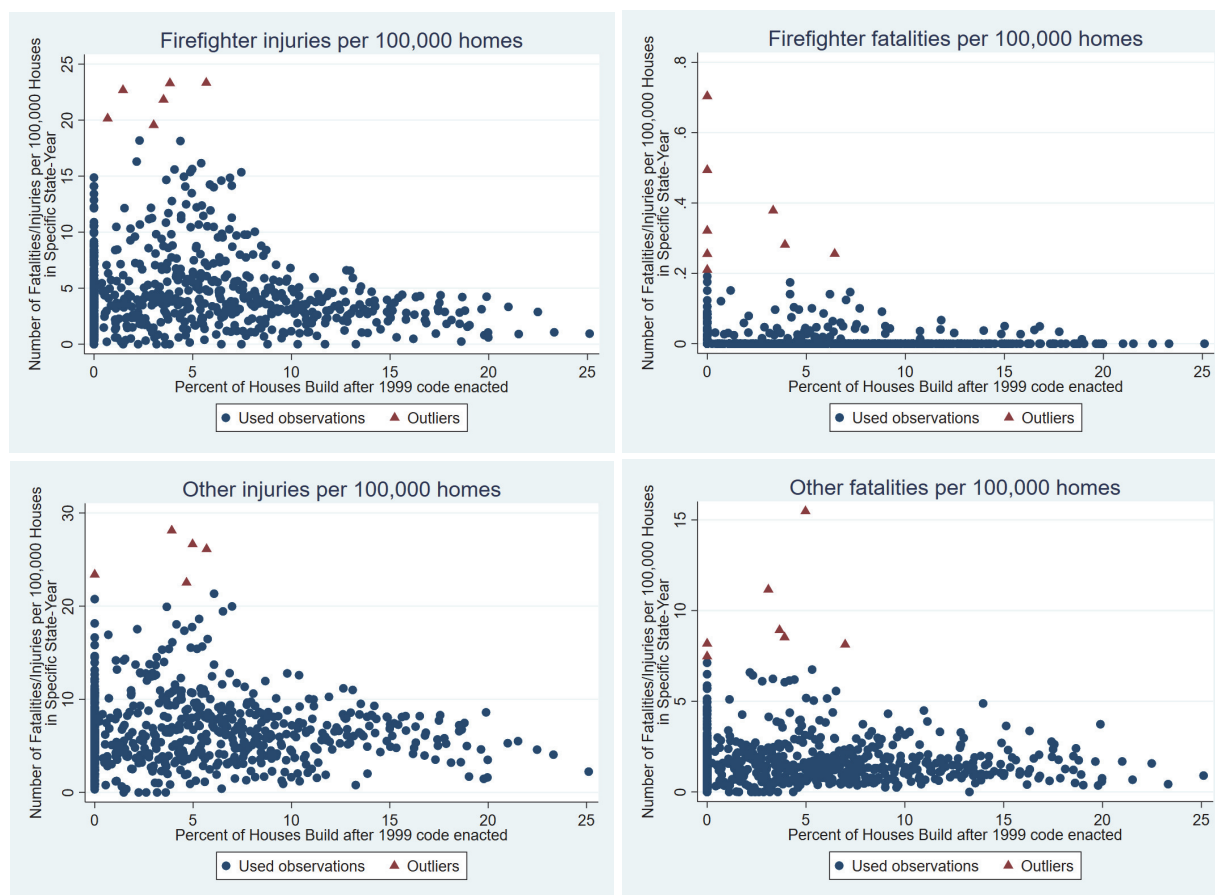


is arbitrary and used for example purposes). Some observations clearly stand out as separate from the rest. For the highest severity fires, the two most severe outliers correspond to state and year combinations that experienced unusually severe wildfires (101 severe fires per 100,000 homes occurring in Tennessee in 2016, and 49 severe fires per 100,000 homes occurring in Alaska in 2015). Outcomes from years with severe wildfires likely do not reflect on the effectiveness of smoke alarm standards—severe fires occur regardless of the effectiveness of

smoke alarm standards. To consistently focus on years and states where the variation is more likely to reflect smoke alarm standards, we exclude observations where the dependent variable of interest is more than 4 standard deviations from the mean.⁵⁷

Figure B.2 shows the observations for fatalities and injuries that are more than 4 standard deviations from the mean. This figure also makes it clearer why the coefficients for firefighter fatalities are so large: Percentage changes are liable to be quite large because all observations are at or near zero. Most fatalities in NFIRS are residents, not firefighters.

Figure B.2. Outliers in Fatalities and Injuries



⁵⁷ We recognize that the underlying data is heteroskedastic, and thus this exclusion is more likely to drop observations with lower values on the x-axis. We felt that an objective cut-off (here, 4 standard deviations) was preferable to hand-picking outliers. As we note in this appendix, our results are comparable if we include all observations; any bias caused by our process of outlier selection is trivial.

We also examine results from excluding observations where the residual variation after controlling for state and year fixed effects is more than 4 standard deviations from the mean. These residuals are centered on zero, so the exclusion of outliers includes both high and low outcomes. The differences in results between these two methods of controlling for outliers are largely imperceptible.

Chapter 4 presents results that exclude outliers, given our concern about the relevance of those observations. Table B.2 presents the results for fire spread that include these outliers. As suggested by Figure B.1, the coefficients are larger for fires that spread beyond the building of origin and for fires confined to the room of origin, but all coefficients remain insignificant. The results are otherwise similar; we find no statistically significant relationship between the proportion of housing built since a residential building code update and the number of reported fires per 100,000 homes.

Similarly, Table B.3 presents the results for injuries and fatalities with outliers included. Here the coefficients on the number of firefighter injuries per capita are larger but still statistically insignificant. The results are again otherwise similar.

Table B.2. No Statistically Significant Relationship Between the Proportion of Housing Built Since Code Updates and the Number of Reported Fires, Including Outliers

Fire Spread	1999 Edition	2002 Edition	2007 Edition	2010 Edition
Beyond building of origin	1.6%	1.6%	1.0%	1.0%
Confined to building of origin	1.1%	1.1%	0.9%	0.5%
Confined to floor of origin	1.0%	1.1%	0.8%	0.4%
Confined to room of origin	1.4%	1.5%	1.3%	0.8%
Confined to object of origin	2.4%	2.4%	2.1%	2.1%

NOTE: None of the results is statistically significant at a 95% confidence level when using heteroskedasticity robust standard errors (which are necessary due to heteroskedasticity in this data).

Table B.3. No Statistically Significant Relationship Between the Proportion of Housing Built Since Code Updates and the Number of Reported Injuries or Fatalities, Including Outliers

	1999 Edition	2002 Edition	2007 Edition	2010 Edition
Firefighter injuries per 100,000 homes	0.9%	1.2%	1.3%	1.2%
Firefighter fatalities per 100,000 homes	4.5%	6.4%	5.0%	11.6%
Other injuries per 100,000 homes	0.8%	0.9%	1.1%	0.5%
Other fatalities per 100,000 homes	1.3%	1.4%	1.1%	1.0%

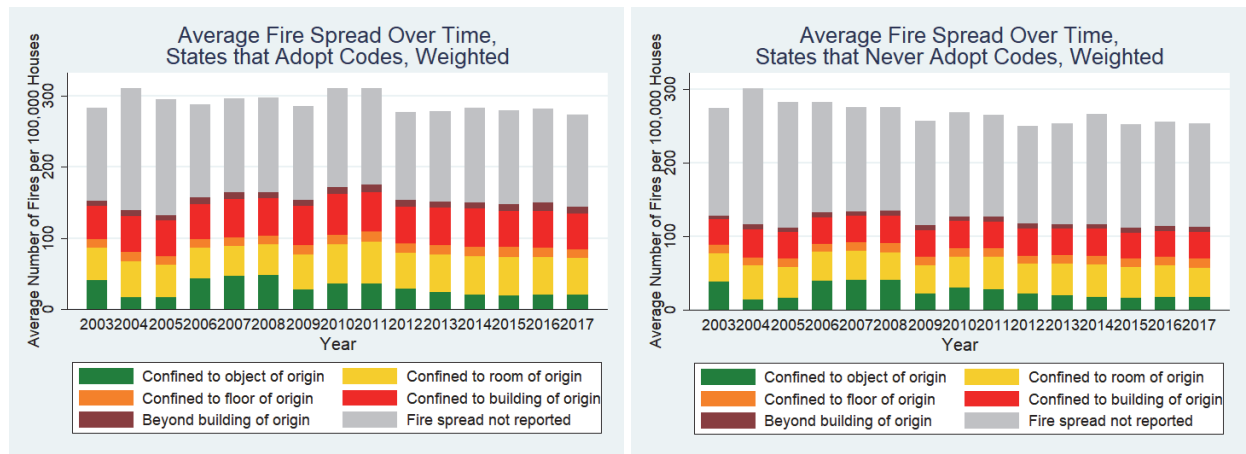
NOTE: None of the results is statistically significant at a 95% confidence level when using heteroskedasticity robust standard errors (which are necessary due to heteroskedasticity in this data).

The Importance of State and Year Fixed Effects

A thoughtful reader might ask why the coefficients in our results are positive, despite the scatterplots in Figure B.1 and Figure B.2 appearing to reflect a slightly downward-sloping trend, if anything. The answer is that once state and year averages are accounted for, the downward-sloping trend disappears.

Figure B.3 highlights the importance of accounting for state and year averages (via fixed effects included in our second-stage Poisson regression). Figure B.3 compares the number of fires and the distribution of severities between states that ever adopt state-wide minimum codes

Figure B.3. States with Minimum Codes Report More Fires but Have a Similar Distribution of Severity



(left) and states that never adopt state-wide minimum codes (right). See Figure 4.2 for a list of which states do and do not adopt state-wide minimum codes. The states that never adopt codes have slightly fewer fires per 100,000 homes (the distribution of severity is similar); these states may choose not to adopt codes in part because they have less need for statewide minimum fire safety codes. Thus state fixed effects are important to avoid erroneously concluding that codes cause more fires. Second, even though the number of fires per capita had radically decreased prior to 2003, there is still a slight decrease over time and notable year-by-year variation in the number of fires. Year fixed effects ensure we separate safety improvements experienced by all states from safety improvements experienced only by states that adopt updated residential building codes.

We did examine the “intensive margin” analysis of only including states that ever adopt codes in the analysis, which effectively excludes many of the observations with x-axis values of zero in Figure B.1 and Figure B.2. The coefficients on the proportion of housing built since updated residential building codes were enacted were smaller and in some cases negative, but all results remained statistically insignificant. State and year fixed effects continue to fully account for any visually suggested downward trend.

Appendix C. Spatial Econometric Model Overview

We use a spatial probit model to better assess the relationship between year built and survivability. The probit model accounts for the bounded nature of survivability—that the likelihood a house is damaged must fall between 0 percent and 100 percent. And spatial methods—namely controlling for the performance of neighboring houses—account for unobserved local conditions such as local fire intensity and exposure to potential structure-to-structure ignition. Including the performance of neighboring houses and other controls helps ensure that the model does not attribute the effects of omitted geographic variables to the house’s age.

Damage to structures is measured discretely: Either a building is damaged, or it is not damaged.⁵⁸ Techniques such as probit models are often used when the dependent variable is discrete.

We use a model based on Anselin (2003) to incorporate spatial interactions between houses into our prediction of whether a house is damaged. Specifically, we identify each house’s five nearest neighbors,⁵⁹ and include the average damage outcome among the five neighboring households as a predictor of damage. This measure reflects both the risks imposed by neighboring housefires and more generally the shared, unobserved risk factors associated with geography. As discussed in Chapter 6, these shared geographic factors could include vegetation, fire intensity, and other factors. Accounting for the average, aggregate impact of these unobserved geographic factors allows us to more accurately measure the relation between house age and fire damage.

Figure C.1 shows neighbor relationships as lines connecting each house with its nearest five neighbors. For the most part, neighbors are located close together, but the graph shows that some isolated houses have neighbors located far away.

We use a probit model to estimate the probability of damage, with damage predicted using binary indicators for the decade in which a house was built, an indicator for whether the home is permanent versus manufactured, and measures of “density” (the number of surrounding homes). We estimate this probit model in two different ways, each of which has different interpretations that bound the overall impact. Our first approach, which we call the “static” model, uses the observed damage outcomes of neighboring homes as an independent variable. The second

⁵⁸ In the DINS data, damage is measured on a discrete scale of four levels of damage. As Figure 4.3 shows, nearly all houses were undamaged or destroyed—few houses suffered partial damage. We also explored models that looked at different damage cutoffs (e.g., grouping undamaged houses with lower levels of damages, similar to the way that Syphard and Keeley [2019] compared lightly damaged houses with heavily damaged houses), but the results were similar.

⁵⁹ Explorations with other definitions of neighbors resulted in qualitatively similar results.

Figure C.1. Neighbor Relationships Between Houses



SOURCE: RAND specification of spatial weights as displayed in GeoDa v. 1.14.0 24, August 2019
(Center for Spatial Data Science, 2021).

approach, which we call the “recursive” model, uses the predicted damage outcomes for neighboring houses instead of the observed damage outcomes, meaning it must be estimated as a simultaneous equation model (because the dependent variable for one observation affects the value of an independent variable for another observation). The differences in treatment of damage to neighboring homes is discussed in Chapter 6. The other independent variable are discussed in further detail below.

The two models can be expressed as follows:

Static Model: $P(\text{DAMAGED}_i = 1|\mathbf{X}_i) = \Phi(\beta_0 + \beta_1\text{BUILT1900}_i + \beta_2\text{BUILT1920}_i + \beta_3\text{BUILT1930}_i + \beta_4\text{BUILT1940}_i + \beta_5\text{BUILT1950}_i + \beta_6\text{BUILT1960}_i + \beta_7\text{BUILT1970}_i + \beta_8\text{BUILT1980}_i + \beta_9\text{BUILT1990}_i + \beta_{10}\text{BUILT2000}_i + \beta_{11}\text{BUILT2010}_i + \beta_{12}\text{PERM}_i + \beta_{13}\text{DENSITY100}_i + \beta_{14}\text{DENSITY1K}_i + \beta_{15} \sum_j \frac{\text{DAMAGED}_j}{5})$

Recursive Model: $P(\text{DAMAGED}_i = 1|\mathbf{X}_i) = \Phi(\beta_0 + \beta_1\text{BUILT1900}_i + \beta_2\text{BUILT1920}_i + \beta_3\text{BUILT1930}_i + \beta_4\text{BUILT1940}_i + \beta_5\text{BUILT1950}_i + \beta_6\text{BUILT1960}_i + \beta_7\text{BUILT1970}_i + \beta_8\text{BUILT1980}_i + \beta_9\text{BUILT1990}_i + \beta_{10}\text{BUILT2000}_i + \beta_{11}\text{BUILT2010}_i + \beta_{12}\text{PERM}_i + \beta_{13}\text{DENSITY100}_i + \beta_{14}\text{DENSITY1K}_i + \beta_{15} \sum_j \frac{P(\text{DAMAGED}_j=1|\mathbf{X}_j)}{5})$.

DAMAGED_i is an indicator variable for whether house i was damaged in the Camp Fire, $\mathbf{X}$ represents all independent variables in the probit regression, $\Phi(x)$ is the standard normal cumulative distribution function, and j is the five nearest neighbors for house i .⁶⁰ The other control variables are as described below.

Year Built

We grouped houses into the decade they were built (houses built before 1920 are grouped together due to a small number of observations for those years). For each house, all variables are zero except for the decade in which the house was built, which is 1. For example, a house that is built in 1984 has $\text{BUILT1980}_i = 1$, and all other variables are zero.

The analysis discussed in Chapter 6 showed that newer homes are on average more survivable.

Permanent Versus Manufactured Homes

Homes are either permanent ($\text{PERM} = 1$) or manufactured ($\text{PERM} = 0$). Previous research, including research by NIST (Maranghides and McNamara, 2016, pp. 64, 116) has found that manufactured homes are more vulnerable to fires igniting underneath the home than permanent homes built on a foundation or over an enclosed crawlspace.

Permanent homes fared better than manufactured homes, with 16 percent of permanent homes undamaged versus only 7 percent of manufactured homes. One potential driver for this difference, as identified previously by NIST research (Maranghides and McNamara, 2016, pp. 64, 116), is construction techniques that allow fires to ignite beneath homes. Permanent homes utilizing pier and beam foundations also allow fires to ignite underneath but these foundations are relatively uncommon.

⁶⁰ Mathematically, this is accomplished through use of a spatial weights matrix, W , which identifies which observations neighbor each other by assigning the respective weight to give each observation. In the static model, this could be written as $\beta_{15} W_i \text{DAMAGED}_i$. The weights matrix, W , is an $N \times N$ matrix where N is the number of observations. The values for W —i.e., the identification of neighbors and their respective weights—are set external to the regression model.

Density

We incorporate two measures of density based on a count of the number of houses within a certain radius of each house in the dataset. A density metric with a radius of 100 m accounts for risks correlated with high levels of density near a house (e.g., automobile-to-structure ignitions). A density metric with a radius of 1 km accounts for larger-scale impacts of density (e.g., houses in Paradise and Magalia have high numbers of houses within 1 km, while houses in more isolated subdivisions, even if dense, have lower numbers of houses within 1 km).

Table 6.2 shows that undamaged structures were in areas with lower housing density. Damaged houses had an average of 8.6 houses located within 100 m, while undamaged houses had an average of 4.69 houses located within 100 m. At 1 km, damaged houses had an average of 518 houses located within 1 km, while undamaged houses had an average of 327 houses located within 1 km.⁶¹

Including explicit measures of density is likely not critical to the modeling because density is inherently accounted for within the spatial lag variable (since neighbors have very similar densities). However, density calculations are relatively straightforward. If density were not included separately, the impacts would likely increase the importance of the spatial lag term, thereby exaggerating the positive feedback loop.

⁶¹ One potential limitation of the density variables—especially the 1 km variable—is that they do not account for homes outside the fire perimeter, which are not included in the data. Homes near the fire perimeter in Magalia and near Chico, where fire lines were held near populated areas, are denser than the variables indicate.

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