Insurance, Economic Incentives and other Policy Tools for Strengthening Critical Infrastructure Resilience: 20 Proposals for Action

Howard Kunreuther
The Wharton School
University of Pennsylvania

Erwann Michel-Kerjan
The Wharton School
University of Pennsylvania

Gina Tonn
The Wharton School
University of Pennsylvania
Corresponding author:
gtonn@wharton.upenn.edu

December 2016

Center for Risk Management and Decision Processes
The Wharton School, University of Pennsylvania

Research conducted as part of the DHS's Critical Infrastructure Resilience Institute

Version for Comments

[THIS PAGE BLANK]

EXECUTIVE SUMMARY

In the U.S., infrastructure is generally becoming less resilient due to decay and deterioration, since investments in maintenance and replacement are insufficient. There is a gap between the preparedness of critical infrastructure and actual risk. The majority of federal disaster assistance funding is spent on repairing public infrastructure, so clearly there is a huge economic reason for improving infrastructure resilience. Furthermore, other infrastructure systems, commercial entities, and individuals rely on public infrastructure, and their disruption can cause significant impacts.

Economic and insured losses from catastrophic events, particularly natural disasters such as hurricanes, earthquakes, and floods, have significantly increased in the past decades. The increased costs are primarily due to a higher degree of urbanization and an increase in the value at risk. The upward trend in losses has had an impact on post-disaster government relief to assist the affected communities in rebuilding destroyed infrastructure and providing temporary housing to displaced victims. In the United States, federal and state governments have played an increasingly important role in providing such assistance, with a significant increase since the mid-1950s. In light of these increasing disaster relief expenditures, this study seeks to identify barriers, challenges, and opportunities for risk reduction in critical infrastructure systems through insurance and market-based incentives.

There is general agreement that improving resilience to reduce future disruptions is a good thing. But while more work is being done to better understand how to make infrastructure more resilient from a physical or cyber perspective, questions related to economic and financial considerations have not been addressed: Who will pay for these resilience investments? What is the best way to finance resilience over the short- and long-terms? Until one can answer these questions, we believe most of the discussion about infrastructure resilience will remain just that—a discussion.

Insurance, as one of the largest industries in the world, can be a catalyst for resilience, as we show in this report. Large losses from natural and man-made disasters (e.g. terrorism) may be insured through traditional insurance products as well as through new financial instruments, such as catastrophe bonds, that transfer some of the risk to investors. We discuss the operation of the insurance market for catastrophe insurance in the United States—the supply side in **section 2**, and the demand side in **section 3**. The concepts of *insurability* and the *cost of capital* are important elements of the insurance market and must be considered in the context of disaster risk management and resilience. In designing insurance mechanisms for improving resiliency one must take into account behavioral factors such as a bias toward maintaining the *status quo* and hence a reluctance to consider new alternatives, and the *availability bias* which leads to an overweighting of recent events in the decision process. Short-run budget constraints must be considered, also.

In recent years, more disaster risk has been transferred directly to investors in the financial markets via instruments such that *catastrophe bonds*, which we discuss in **section 4.** For instance, in the transportation sector both New York's Metropolitan Transit Authority (MTA) and Amtrak have now used these financial protection instruments.

Disaster relief and other forms of state aid can deter both investment in mitigation measures and the purchase of insurance indirectly increasing the need for future aid. The primary barriers to improving infrastructure resilience through insurance and other market-based incentives are illustrated in **section 5** focusing on two sectors: transportation and energy utilities.

Section 6 discusses our twenty proposals (listed below) for utilizing insurance and other policy tools to foster resilience based on our interaction and interviews with leaders of the insurance and reinsurance industry, and infrastructure owners and operators, along with findings from previous research. We will examine these proposals in more detail during the coming year.

Twenty Proposals to Improve Infrastructure Resilience though Insurance, Economic Incentives and other Policy Tools

|	
#1	Develop modern risk assessment capability
#2	Frame the risk differently to change behavior
#3	Build credible worst case scenarios
#4	Structure insurance premiums to reflect risk
#5	Use insurance to incentivize resilience investments
#6	Design new multi-year insurance contracts
#7	Support public-private partnerships for catastrophe insurance
#8	Address insurance affordability issues
#9	Increase resilience through means-tested insurance vouchers
#10	Incentivize resilience improvements through regulated rate filings
#11	Incentivize resilience via enhanced bond ratings
#12	Issue "resilience bonds" as a dedicated asset class
#13	Encourage insurers to invest in resilience bonds
#14	Offer public-sector long-term mitigation grants and loans
#15	Establish and finance a dedicated National Resilience Fund
#16	Offer tax incentives at the local, state, and federal government levels
#17	Adopt and enforce land ordinances and zoning codes that promote resilience
#18	Establish resilience standards and seals of approval
#19	Modify the Stafford Act so public infrastructure are better insured
#20	Examine private insurance capacity to insure public infrastructure on a larger scale

1.1. Natural and Man-Made Disasters Are Becoming More Costly

Economic and insured losses from natural catastrophes such as hurricanes, earthquakes, and floods have increased significantly in recent years. Hurricane Katrina, which severely struck Louisiana and Mississippi in the United States in August 2005, resulted in massive flooding after the inadequate levee system in New Orleans failed. Over 1,300 people died, millions were displaced, and the response by the U.S. Federal Emergency Management Agency was perceived as insufficient. Hurricane Katrina was a Category 3 hurricane when it made landfall but its strength, combined with the failure of the flood protection system, led to economic losses in the range of $150 to $200 billion—an historical record in the United States for a natural disaster. Superstorm Sandy, which hit the Northeastern part of the United States at the end of October 2012, caused an estimated $80 billion in economic losses to residences, business owners, and infrastructure owners. Sandy, the second most costly natural disaster in the United States after Hurricane Katrina, was not even classified as a hurricane when it made landfall. If its wind speed had been higher at landfall, losses could have been dramatically more important given the high concentration of assets in the affected areas.

Conventional wisdom holds that major accidents and disasters are low-probability events. But when you look at a whole state or country, as insurers normally do, such events have a relatively high chance of occurring somewhere during a short time period. It is somewhat sobering to learn that there is a 1 in 6 chance that at least $10 billion dollars of insured property will be destroyed by hurricanes somewhere in Florida next year. This is equivalent to the likelihood of getting the number 3 in one toss of a die—hardly a low probability. If we extend the time horizon from one year to 10 years while keeping the population of Florida constant, the likelihood of at least one hurricane causing damage exceeding this amount is greater than 5 in 6. With economic development in coastal areas of Florida and the projected increased intensity of hurricanes due to global warming, we are almost certain to experience a disaster with losses exceeding $10 billion in Florida in the next decade (Kunreuther and Michel-Kerjan, 2011).

Worldwide, economic losses from natural catastrophes increased from $528 billion in the decade 1981–1990, to $1,197 billion during 1991–2000, and $1,213 billion during 2001–2010. In 2011 alone, economic losses amounted to over $400 billion, in large part due to the March 2011 Japan earthquake and resulting tsunami; 2012 brought another $170 billion in economic losses (Munich Re, 2013). Figure 1.1 depicts the evolution of the direct economic losses and the insured portion from great natural disasters over the period 1980–2015.

Figure 1.1 Natural catastrophes worldwide 1980–2015: Overall and insured losses ($ billion).
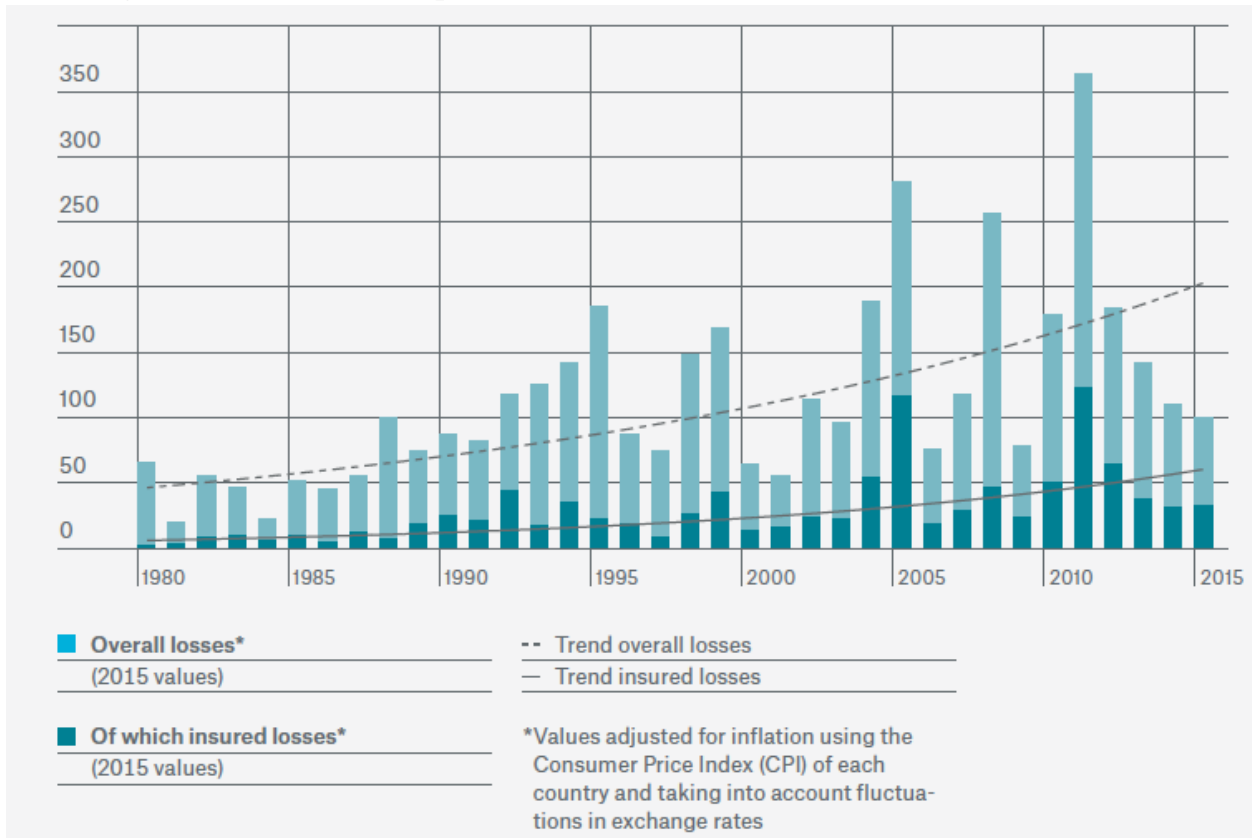
Sources: Munich Re

Insured losses have dramatically increased as well. Between 1970 and the mid-1980s, annual insured losses from natural disasters worldwide (including forest fires) were only in the $3 billion to $4 billion range. Hurricane Hugo, which made landfall in Charleston, South Carolina, on September 22, 1989, was the first natural disaster in the United States to inflict more than $1 billion of insured losses, with insured losses of $4.2 billion (1989 prices). During the period 2001 to 2010, insured losses from weather-related disasters alone averaged $30 billion annually (Swiss Re, 2011).

Table 1.1 ranks the 25 most costly *insured* catastrophes that occurred in the world over the period 1970–2016. With the exception of insured losses from the 9/11 terrorist attacks, all of the events were natural disasters. The data reveals that eighteen of these disasters occurred since 2001, with almost two-thirds in the United States, due in part to the high concentration of value at risk and the high degree of insurance penetration compared to less developed countries. Note that we are not considering financial crises here and focus solely of the insured portion of the loss.

Table 1.1: The 25 Most Costly Insured Catastrophes in the World, 1970–2016 (2016 prices)

$ Billion	Event	Victims (Dead and Missing)	Year	Area of Primary Damage
80.0	Hurricane Katrina; floods	1,836	2005	USA, Gulf of Mexico
45.0	9/11 terrorist attacks	3,025	2001	USA
37.6	Earthquake (M 9.0) and tsunami	19135	2011	Japan
36.9	Hurricane Sandy; floods	237	2012	USA
27.6	Hurricane Andrew	43	1992	USA, Bahamas
22.9	Northridge Earthquake (M 6.6)	61	1994	USA
22.7	Hurricane Ike; floods	136	2008	USA, Caribbean
16.5	Hurricane Ivan	124	2004	USA, Caribbean
16.1	Floods; heavy monsoon rains	815	2011	Thailand
16.1	Earthquake (M 6.3); aftershocks	181	2011	New Zealand
15.5	Hurricane Wilma; floods	35	2005	USA, Gulf of Mexico
12.5	Hurricane Rita	34	2005	USA, Gulf of Mexico, et al.
11.6	Drought in the Corn Belt	123	2012	USA
10.3	Hurricane Charley	24	2004	USA, Caribbean, et al.
10.0	Typhoon Mireille	51	1991	Japan
9.0	Hurricane Hugo	71	1989	Puerto Rico, USA, et al.
8.8	Earthquake (M 8.8); tsunami	562	2010	Chile
8.6	Winter Storm Daria	95	1990	France, UK, et al.
8.4	Winter Storm Lothar	110	1999	France, Switzerland, et al.
7.8	Storms; over 350 tornadoes	350	2011	USA (Alabama et al.)
7.6	Major tornado outbreak	155	2011	USA (Missouri et al.)
7.1	Winter Storm Kyrill	54	2007	Germany, UK, NL, France
6.5	Storms and floods	22	1987	France, UK, et al.
6.5	Hurricane Frances	38	2004	USA, Bahamas
6.3	Hurricane Irene	55	2011	USA, Caribbean

As discussed during the workshop on Managing Critical Infrastructure Dependencies held at Northeastern University in November 2016, Superstorm Sandy forced a five-day closure of the Port of Boston, operated by the Massachusetts Port Authority (Massport). The length of the outage was due largely to a lack of power. The roads in and out of the port were flooded, which halted the movement of goods and fuel. The port is a hub for fuel transport in the northeast, and downtime at Massport had far-reaching economic consequences. In New York City, storm surge and flooding associated with Sandy resulted in about $5 billion in damages to New York's Metropolitan Transit Authority (MTA), of which roughly $1 billion was insured. Flynn (2015) notes that Sandy revealed "the consequences of not having performance-based engineering approaches for managing the risk of disruption at the component, system, and network-of-systems levels. This problem is prevalent both within any given lifeline sector, and amongst those sectors such as the interfaces across power,

transportation, communication, and healthcare." Cascading impacts, outdated codes and standards, and insufficient economic and policy incentives resulted in significant critical infrastructure failures during Sandy (Flynn 2015).

Infrastructure is vulnerable to other interdependencies beyond natural disasters. For example, the blackout in August 2003, caused by an electricity surge crippled parts of the Northeast U.S. and Canada and caused cascading effects in other critical infrastructure including transportation and communication systems. Fifty million North Americans were deprived of electricity and the economic effect of the blackout was estimated at $6 billion, with financial impacts seen across the industrial, commercial, and public sectors (ELCON 2004). These types of events underscore the need for improved resiliency in our nation's critical infrastructure systems.

1.2. The Question of Attribution

The increased costs of disasters in recent years are primarily due to a higher degree of urbanization and an increase in the value at risk. In 1950, approximately 30 percent of the world's population lived in cities. In 2000, about 50 percent of the world's population (6 billion) resided in urban areas. Projections by the United Nations (2008) show that by 2025, this figure will have increased to 60 percent based on a world population estimate of 8.3 billion people.

In the United States in 2003, 53 percent of the nation's population (153 million people), lived in the 673 U.S. coastal counties, an increase of 33 million people since 1980, according to the National Oceanic Atmospheric Administration (Crossett et al. 2004). Yet coastal counties, excluding Alaska, account for only 17 percent of land area in the United States. In hazard-prone areas, this urbanization and increase in population translate into greater concentration of exposure and hence a higher likelihood of catastrophic losses from future disasters.

This increased vulnerability is best understood in an historical context. It is possible to calculate the total direct economic cost of catastrophes in the past century adjusted for inflation, population, and wealth. For example, a study by Pielke et al. (2008) normalizes mainland U.S. hurricane damage for the period 1900–2005. They show that the hurricane that hit Miami in 1926 would have been almost twice as costly as Hurricane Katrina had it occurred in 2005, and the Galveston hurricane of 1900 would have had total direct economic costs as high as those from Katrina. We are very likely to see even more devastating disasters in the coming years because of the ongoing growth in values located in risk-prone areas.

Another element to consider in determining how to adequately manage and finance catastrophic risks is the possible impact of a change in climate on future weather-related catastrophes. Between 1970 and 2004, storms and floods were responsible for over 90 percent of the total economic costs of weather-

related extreme events worldwide. Storms (hurricanes in the U.S. region, typhoons in Asia, and windstorms in Europe) contributed to over 75 percent of insured losses. In constant prices (2004), insured losses from weather-related events averaged $3 billion annually between 1970 and 1990 and then increased significantly to $16 billion annually between 1990 and 2004 (Association of British Insurers, 2005). In 2005, 99.7 percent of all catastrophic losses worldwide were due to weather-related events (Mills and Lecomte 2006).

One of the expected effects of global warming will be an increase in hurricane intensity. This increase has been predicted by theory and modeling, and substantiated by empirical data on climate change. Higher ocean temperatures lead to an exponentially higher evaporation rate in the atmosphere, which increases the intensity of cyclones and precipitation (IPCC 2011). An increase in the number of major hurricanes over a shorter period of time is likely to translate into a greater number hitting the coasts, with a greater likelihood of damage to residences and commercial buildings today than in the 1940s. Superstorm Sandy has stimulated studies on ways that communities can be more prepared for future disaster damage as well as highlighting the need for a suite of policy tools including insurance to address the climate change problem. (New York City Panel on Climate Change 2015).

Man-made events have had their impact on direct damage and indirect losses as well: the 2010 oil spill in the Gulf of Mexico was the most damaging environmental disaster in recent history. The 2011 Japanese earthquake and tsunami was also devastating, partly because it caused a severe a nuclear accident at the Fukishima plant. Moreover, the threat of terrorist attacks on U.S. soil remains real more than 15 years after September 11, 2001.

1.3. Increasing Governmental Disaster Relief

The upward trend in losses has had an impact on post-disaster relief to assist the affected communities in rebuilding damaged and destroyed infrastructure. Disaster relief buys votes (DeJanvry 2015), whereas government requirements for risk reduction measures may be less popular. In the United States, federal and state governments have played an increasingly important role in providing such assistance. Under the current U.S. system, the governor of the state(s) can request that the president declare a "major disaster" and offer special assistance if the damage is severe enough, with the amount of aid determined by Congress. A look at the number of U.S. presidential disaster declarations since 1953 clearly reveals an upward trend (see Figure 1.2). It is worth noting that floods have affected more people and triggered more economic damage than any other natural disaster around the world and here in the United States. In fact, about two-thirds of all presidential disaster declarations between 1953 to 2015 were flood-related.

Figure 1.2. Evolution of the Annual Number of U.S. Presidential Disaster Declarations. 1953-2011
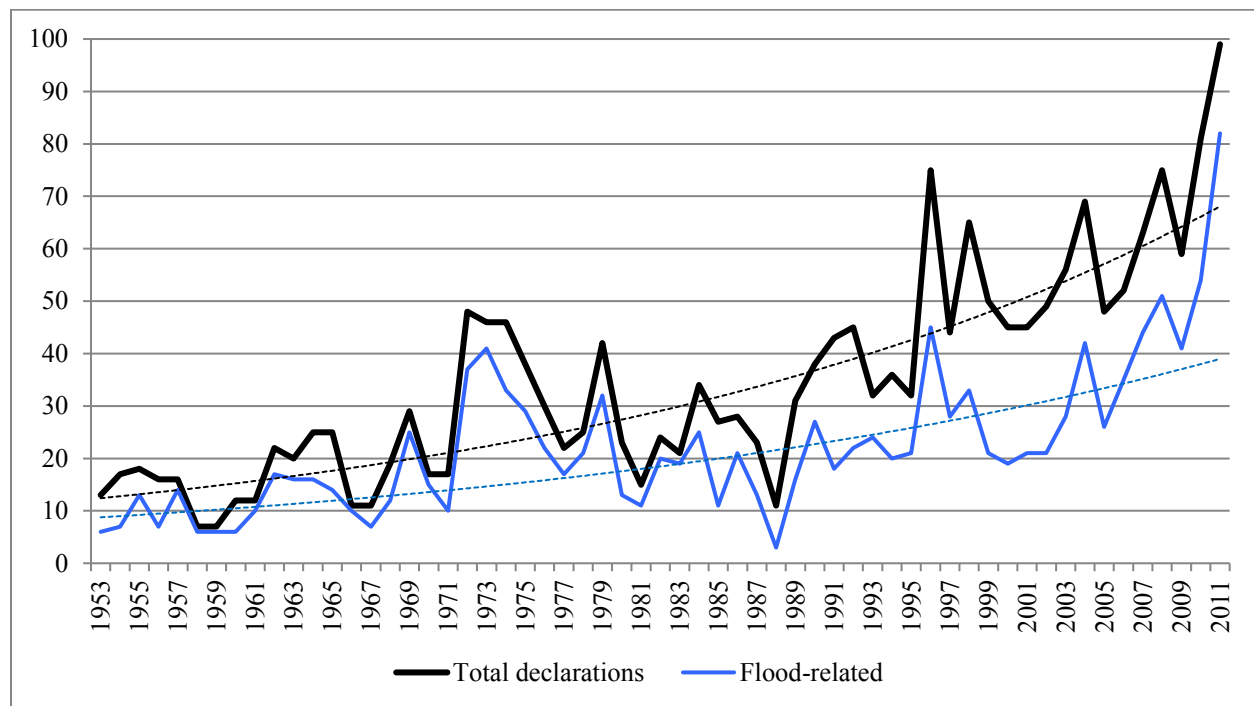
Sources: Michel-Kerjan, E., and H. Kunreuther, *Science*, 2011

Overall, the number of presidential disaster declarations has dramatically increased over time, from 191 declarations over the decade 1961–1970 to 597 for the period 2001–2010 (Michel-Kerjan and Kunreuther 2011). Figure 1.2 also reveals that many of the peak years correspond to presidential election years. This is consistent with research that reveals that presidential election years spur disaster assistance. Four salient examples are the Alaska earthquake (March 1964), Tropical Storm Agnes (June 1972), Hurricane Andrew (September 1992), and the four Florida hurricanes (August–September 2004). In 1996 and 2008 (both presidential election years) there were 75 presidential declarations. This record number was exceeded in 2010 when there were 81 major disaster declarations, and again in 2011 with 99 declarations.

There has been a significant change in the role that the federal government has played in providing disaster relief since the mid-1950s. Prior to that time the Federal government played a minor role in providing assistance. As David Moss (2010) notes:

> "*Congress provided assistance to the victims of a major fire in New Hampshire as early as 1803, and historians have counted 128 specific acts of Congress providing ad hoc relief for the victims of various disasters over the years 1803 to 1947. Nevertheless, disaster relief was not generally viewed as an ongoing federal responsibility in the United States until well into the twentieth century*" (p. 152).

This view was also shared by Kunreuther and Miller (1985) who indicated more than 30 years ago that:

> "*The role of the federal government with respect to hazards has been changing over the past 30 years. Although Congressmen and federal agencies have become more concerned with finding ways to help communities struck by severe disasters, there has also been a realization that government has been viewed as the protector of risks in ways that would have been unthinkable 50 years ago*" (p. 148).

The more pronounced role of the federal government in assisting disaster victims can also be seen by examining several major disasters occurring in the past 50 years. Figure 1.3 shows the proportion of economic losses paid by the government from five major hurricanes hitting US landfall during the period 1955-2012. Media coverage in the immediate aftermath of catastrophes often raises compassion for victims of the tragedy. The expectation of governmental funding results in economic disincentives for people and businesses to reduce their own exposure and/or purchase proper insurance coverage (Michel-Kerjan and Volkman Wise 2011).

Figure 1.3. Proportion of Economic Losses Paid by the U.S. Government for Selected Disasters
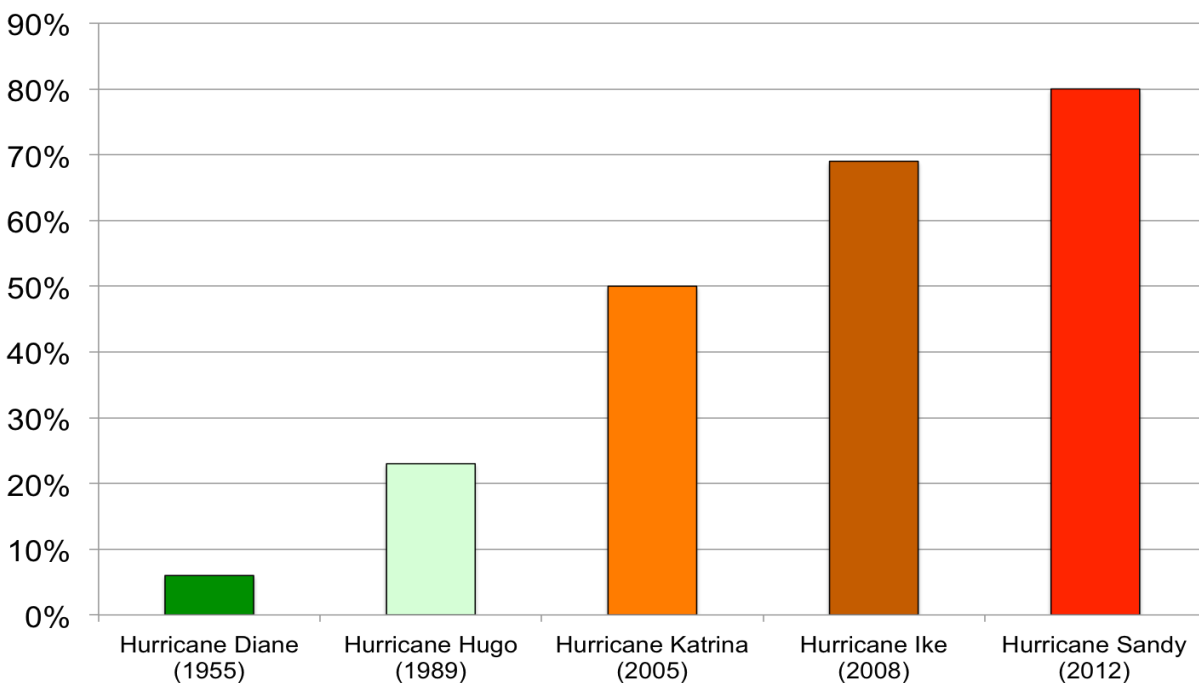
Sources: Michel-Kerjan (2013)

If individuals or organizations assume that they will be bailed out after a disaster, they have less incentive to purchase insurance or avoid locating in high-risk areas. In fact, governmental disaster relief is usually earmarked to rebuild destroyed public infrastructure, not as direct aid to the victims.

To the extent that a large portion of such disaster relief goes to the states and is then given to communities, post-disaster assistance also distorts the incentives of state and local governments to pre-finance their disaster losses through insurance and other mechanisms.

The Stafford Act of 1988 authorizes the delivery of federal technical, financial, logistical, and other assistance to states and localities during Presidentially declared major disasters or emergencies. The Federal Emergency Management Agency (FEMA) coordinates administration of disaster relief resources and assistance to states to help repair and restore damage to infrastructure and public facilities such as schools and hospitals. Funding is normally divided into a 75 percent federal share and 25 percent state share; For major catastrophes, the federal share may be raised as was the case after Hurricane Katrina when the federal government provided 100 percent of the assistance to the stricken Gulf Coast areas.

In recent years, the insurance industry has grown to become one of the largest industries in the world. It has a critical role to play in providing incentives for owners of critical infrastructures, others firms and individual to invest in resilience. But it is also important to better appreciate the reality of how the supply of insurance work and the reality of the constraints insurers face.

2.1. Factors Influencing the Supply of Insurance

Insurance is said to be priced at an actuarially fair rate when the premium charged to cover a risk of losing L with a probability p equals the expected loss (i.e., pL). An insurer will normally charge an additional administrative cost to cover its own expenses and generate a profit. Providing an attractive return to shareholders is obviously a key differentiating point between private insurers and public insurance. A state-run insurer or a federal government insurance program is typically designed to break even, not to generate profits. (More on this when we discuss the cost of capital.)

If insurance premiums are not actuarially fair, a risk-neutral party (a resident, a critical infrastructure owner) would not be interested in purchasing coverage unless required to do so. On the other hand, a risk-averse party would be willing to pay a higher price than the expected loss to avoid the negative consequences of a large loss.

An insurer normally relies on risk pooling and the law of large numbers when providing coverage against a specific risk. If the risks are independent and there are a significant number of policyholders, then the variance in the expected loss is very small so the insurer can estimate with some degree of accuracy how large its annual claims payments will be *on average.*

A benchmark model of insurance supply assumes that insurance companies are maximizing long-run expected profits for their owners in a competitive insurance market. In this environment there are many insurance firms, each of whom is free to charge any premium for a prespecified amount of coverage. The assumption of competition implies that their premiums will be just enough to allow the insurers to cover their costs and make a reasonable profit.

Potential customers and the insurers are assumed to have accurate information on the likelihood of a loss and its consequences. In this idealized world, virtually every uncertain event of concern would be insured to some extent if the administrative cost of furnishing coverage was not high and consumers were sufficiently risk averse and maximized their expected utility (Arrow 1963).

As indicated above, private insurers need to make a profit and generate a sufficient return to their owners to make this an attractive investment. An important element in this regard is the concept of

insurability. Two conditions must be met before insurance providers are willing to offer coverage against an uncertain event. The first is the ability to identify and quantify, or at least estimate, the chances of the event occurring and the extent of losses likely to be incurred. The second condition is the ability to set premiums for each potential customer or class of customers at prices that provide a competitive return at the assumed level of risk.

If both conditions are satisfied, a risk is considered to be *insurable*. But it still may not be profitable. In other words, it may be impossible to specify a premium for which there is sufficient demand and incoming revenue to cover the development, marketing, operating, cost of holding capital (see discussion below) and costs of claims processing, and yield a net positive profit over a prespecified time horizon. In such cases, the insurer will not want to offer coverage against this risk. In addition, as discussed below, state regulations often limit insurers in their premium-setting process. Competition can also play a role in determining what premium can be charged. Even in the absence of these influences, an insurer must consider problems associated with asymmetry of information (*adverse selection* and *moral hazard*), and degree of *correlation of the risk* in determining what premium to charge. We briefly examine each of these factors in the following subsections.

Adverse Selection

If the insurer cannot differentiate the risks facing two groups of potential insurance buyers and if all buyers know their own risk, then the insurer is likely to suffer greater losses if it sets the same premium for both groups by using the entire population as a basis for this estimate. If only the highest risk group is likely to purchase coverage for that hazard and the premium is below its expected loss, the insurer will have a portfolio of "bad" risks. This situation, referred to as *adverse selection*, can be rectified by the insurer charging a high enough premium to cover the losses from the bad risks. In so doing, the good risks might purchase only partial protection or no insurance at all, because they consider the price of coverage to be too expensive relative to their risk.

This was the argument made by private insurers regarding the noninsurability of flood risk that led to the creation of the National Flood Insurance Program (NFIP) in 1968. Indeed, insurers thought that families who had lived in a specific flood-prone area for many years had a much better knowledge of the risk than any insurer would have gained unless it undertook costly risk assessments. Likewise, certain businesses may have a much better knowledge about the risk they are exposed to, and their degree of preparedness for a loss than will the insurer.

Moral Hazard

Moral hazard refers to an increase in the expected loss (probability or amount of loss conditional on an event occurring) due to individuals and firms behaving more carelessly as a result of purchasing insurance. A firm with insurance protection may alter its behavior in ways that increase the expected loss relative to what it would have been without coverage. If the insurer cannot predict this behavior and relies on past loss data from uninsured firms to estimate the distribution of claim payments, the resulting premium is likely to be too low to cover expected losses. The introduction of deductibles,

coinsurance or upper limits on coverage can be useful tools in reducing moral hazard, by encouraging insureds to engage in less risky behavior, as they know they will incur part of the losses from an adverse event.

Correlated Risks

The potential for highly correlated losses from extreme events has an impact on the tail of the distribution and normally requires the insurer to hold additional capital in liquid form to protect itself against large losses. Insurers normally face spatially correlated losses from large-scale natural disasters. State Farm and Allstate paid $3.6 billion and $2.3 billion in claims, respectively, in the wake of Hurricane Andrew in 1992 due to their high concentration of homeowners' policies in the Miami-Dade County area of Florida. Given this unexpectedly high loss, both companies began to reassess their strategies of providing coverage against wind damage in hurricane-prone areas (Lecomte and Gahagan 1998).

Hurricanes Katrina and Rita, which devastated the U.S. Gulf Coast in August and September 2005, had dramatic impacts on several lines of insurance, notably property damage and business interruption. Edward Liddy, chairman of Allstate, which provided insurance coverage to 350,000 homeowners in Louisiana, Mississippi and Alabama, shortly after Katrina declared:

> "… extensive flooding has complicated disaster planning … and the higher water has essentially altered efforts to assess damage. We now have 1,100 adjusters on the ground. We have another 500 who are ready to go as soon as we can get into some of the most-devastated areas. It will be many weeks, probably months, before there is anything approaching reliable estimates" (Francis 2005).

The Cost of Capital: A Key Factor of Disaster Insurance

The importance of the *cost of capital* as a requisite for private insurers to secure an adequate rate of return to their shareholders is often not sufficiently understood. In particular, the prices charged for disaster insurance must be high enough not only to cover the expected claims costs and other expenses, but also the costs of allocating capital to underwrite this risk. That is, the capital that insurers must set aside to pay expected claims and thus maintain their credit rating needs to bring an attractive enough return to justify its having been held that way. Because large amounts of capital are needed to underwrite catastrophe risk, the resulting premium will be high relative to loss expenses.

The price of insurance is thus very sensitive to the ratio of the amount of capital to expected liability, needed to preserve one's credit rating. A ratio of 1 is normal for the combined books of business of many property liability insurers. However, for catastrophic risk, with its very large tail risk (which severely affects the insurer's credit risk), the capital to liability ratio needs to be higher. Indeed, the capital-to-liability ratio depends on volatility of the catastrophe liability and its correlation with the insurer's remaining portfolio.

For the catastrophe risk premium for a critical infrastructure owner, this may translate into a loading factor λ—on top of the expected loss E(L)—perhaps approximately 0.5 to 1.0; that is premium = $(1 + \lambda)$E(L). Thus the premium would be 150 or 200 percent of the expected loss. This does not reflect undue profitability, but simply the costs of developing the insurance product and marketing it as well as the cost of holding liquid capital and the purchase of reinsurance to pay insured claims in the case of a catastrophes o

There are other considerations that can dramatically increase the cost of capital, notably the impact of double taxation. Harrington and Niehaus (2001) have simulated the tax burden over many parameters and show that tax costs alone can reasonably be as much as the claim cost and lead to further increases in premiums. When we account for all these factors (i.e., high capital inputs, transaction costs and taxes), catastrophe insurance premiums often are several multiples of expected claims costs.

The Role of Rating Agencies

Rating agencies have paid increasing attention to the impact that catastrophic risks will have on the financial stability of insurers and reinsurers. A firm's rating will affect its ability to attract business and hence, its pricing and coverage decisions. To illustrate how ratings are determined, consider the rating agency, A.M. Best, which undertakes a quantitative analysis of an insurer's balance sheet strength, operating performance and business profile. Evaluation of catastrophe exposure plays a significant role in the determination of ratings, as these are events that could threaten the solvency of a company. Projected losses from disasters occurring at specified return periods (a 100-year windstorm/ hurricane or a 250-year earthquake) and the associated reinsurance programs to cover them are two important components of the rating questionnaires that insurers are required to complete.

For several years now, A.M. Best has been requesting such information for natural disasters. Their approach has been an important step forward in the incorporation of catastrophic risk into an insurer's capital adequacy requirements. Until recently, the rating agency has been including probable maximum loss (PML) for only *one* of these severe events (100-year windstorm/250-year earthquake, depending on the nature of the risk the insurer was mainly exposed to) in its calculation of a company's risk-adjusted capitalization.

In 2006, A.M. Best introduced a second event as an additional stress test. The PML used for the second event is the same as the first event in the case of hurricane (a 1-in-100 year event; the occurrence of one hurricane is considered to be independent of the other one). If the main exposure facing the insurer is an earthquake, the second event is reduced from a 1-in-250 year event to a 1-in-100 year event. These new requirements have increased the amount of risk capital that insurers have been forced to allocate to underwrite this risk and have made them more reluctant to provide this coverage unless they are able to increase premiums sufficiently to reflect these additional costs.

Standard and Poor's, another rating agency, has also revised criteria for measuring catastrophic risk which traditionally has been based on premium charges. But the new criteria measure catastrophic risk based on exposure of the insurer. In the past, only reinsurers received a specific "catastrophe" charge. This includes an exposure-based capital charge for insurers similar to what it does for reinsurers based on net expected annual aggregate property losses for all perils at 1 in 250 year return period. And Moody's has adjusted the industry loss exceedance curves used in its risk adjusted capital model for U.S. companies to reflect the recent storm activity.

The Role of Brokers

The commercial insurance we mainly focus on in the report is typically serviced by insurance brokers who link firms seeking financial protection with those that supply coverage. The broker can facilitate transactions, and help critical infrastructure owners better understand their risk and insurance solutions available on the market. Brokers can also help with the issuance of dedicated alternative risk transfer instruments (see section 3.4 below). For medium to large businesses, the broker normally represents the insurance buyer. Brokers can also play an important role in advising clients in risk and crisis management strategies.

2.2. Behavioral Characteristics of Insurers

There is growing evidence in the literature that insurance firms often deviate from the ideal benchmark supply model for several reasons stemming from behavioral factors.

The ambiguities associated both with the probability of an extreme event occurring and the resulting outcomes raise a number of challenges for insurers with respect to pricing their policies. Actuaries and underwriters both utilize rules of thumb that reflect their concern about those risks where past data do not indicate with precision what the loss probability is. Consider estimating the premium for a public utility to homes in New Orleans from future hurricanes. Actuaries first use their best estimates of the likelihood of hurricanes of different intensities to determine an expected annual loss to the property and contents of a particular residence. When recommending a premium that the underwriter should charge, they increase this figure to reflect the amount of perceived ambiguity in the probability of the hurricanes or the uncertainty in the resulting losses. More specifically, if the premium for a nonambiguous risk is given by z, then an actuary will recommend a premium of $z' = z(1 + \alpha)$ where α reflects the degree of ambiguity regarding the risk (Kunreuther 1989).

Underwriters then utilize the actuary's recommended premium as a reference point and focus on the impact of a major disaster, on the probability of insolvency, or on some prespecified loss of surplus to determine an appropriate premium to charge. In 1973, Insurance Commissioner James Stone of Massachusetts suggested that an underwriter who wants to determine the conditions for a specific risk to be insurable will focus on keeping the probability of insolvency below some threshold level ($q*$) rather than trying to maximize expected profits (Stone 1973). From discussions with insurance underwriters today, this safety-first model still characterizes their behavior.

The safety-first model proposed by Commissioner Stone explicitly concerns itself with the likelihood of insolvency when determining whether to provide insurance against a particular risk and, if so, how much coverage to offer and what premiums to charge. Suppose that the insurer sets $q* = 1/250$. This implies that it will want to set premiums so that the likelihood of the insurer suffering a catastrophic loss is no greater than 1/250. The safety-first model also implies that insurers may not pay attention to events whose likelihood of causing insolvency to the insurer is below $q*$.

Actual insurer behavior often seems to follow a safety-first type model rather than the benchmark model of maximizing expected profit. The empirical evidence based on surveys of underwriters supports the hypothesis that insurers will set higher premiums when faced with ambiguous probabilities and uncertain losses for a well-specified risk. (Kunreuther et al. 1993) A web-based experiment reveals that when seeking advice from multiple advisors, insurers are sensitive to whether these experts agree or disagree with each other with respect to a specific forecast and/or in their recommendations for actions and charge higher premiums when faced with ambiguity than when the probability of a loss is well specified (risk) (Cabantous et al. 2011).

For risks we are studying here as part of the work with DHS's CIRI, uncertainty and ambiguity is a real issue. What is the probability distribution of a large-scale devastating cyber-attack on the transportation system somewhere in the Northeast corridor in 2017? It is hard to determine with a high degree of certainty and hence insurers cannot provide insurance coverage at a price they can justify to owners and operators solely based on risk assessment.

We start this section by outlining a benchmark model of demand for insurance by consumers using the concepts of expected utility [E(U)] theory and compares this normative theory with two descriptive models: prospect theory and a goal based model of choice. The section concludes by examining actual behavior by insurers that does not conform to the E(U) and explains these anomalies using concepts from behavioral economics.

3.1. A Benchmark Model of Demand: Expected Utility Theory[1]

The benchmark model of demand is based on the assumption that insurance buyers maximize their expected utility. Decision-makers purchase insurance because they are willing to pay a certain small premium to avoid an uncertain large loss. Expected utility theory tells us that risk-averse organizations are willing to purchase insurance at premiums that exceed their expected loss. A hypothetical example is the consumer who is willing to pay $12 annually to insure against a loss of $100 that has a 1 in 10 chance of occurring. The expected loss under that scenario is $10. The additional $2—the risk premium—reflects the extra amount above the expected loss the consumer is willing to pay for insurance. For the same expected loss, the risk premium will increase should the gamble involve a potentially larger loss and a smaller probability (for example, 1 in 100 chance of losing $1,000) because of the diminishing marginal utility of money—a way of characterizing their attitude toward financial risk. In other words, the 1,000[th] dollar of loss reduces utility more than the 100th dollar of loss for a risk-averse consumer.

The above example assumes that the decision-maker is considering a choice between purchasing insurance that will cover the entire loss should the untoward event occur, or remaining uninsured. A more realistic example would give the decision-maker a choice as to how much insurance to purchase, for example, whether to cover 100 percent of a possible loss or only 70 percent. The premiums for lower amounts of coverage obviously will be less than if one is fully protected. An organization decides how much insurance to purchase by trading off the higher expected loss for less than full coverage with the cost of paying higher premiums for more protection.

The next two subsections discuss models of demand for insurance that may make different predictions regarding consumer behavior than the expected utility model: prospect theory and a goal-based model of choice. While the research in some cases pertains to individual decision-making, the same behaviors are often observed in organizations such as the critical infrastructure systems of interest in this report.

---

[1] This section builds on Kunreuther and Michel-Kerjan (2014).

3.2. A Descriptive Model of Choice: Prospect Theory

Daniel Kahneman and Tversky (1979) developed prospect theory as a model to describe how individuals make choices in the face of uncertainty. One of its central features is the concept of a reference point that normally reflects the individual's current status when approaching a specific decision. Insurance decisions usually are made when a policy expires and one has to decide on whether to renew it, or when an insured individual is considering purchasing coverage, as in the case when a homeowner buys a house in California and is considering whether to purchase earthquake insurance. In either case, the reference point is likely to be the status quo at the time one makes the decision: having insurance and deciding to renew or cancel a policy, or not having insurance and deciding whether to buy coverage or remain uninsured.

The value function

In analyzing the decision to buy insurance, prospect theory emphasizes the changes in wealth from a given reference point, rather than the final wealth level that forms the basis for choices using the benchmark expected utility model. Prospect theory also values losses differently than it values gains. Empirical investigations show that individuals tend to experience the pain of a loss approximately twice as strongly as they enjoy gains of the same magnitude (Tversky and Kahneman 1991). In other words, a certain loss of $20 will be viewed as considerably more painful than the positive feeling from a gain of $20. Stated simply, people tend to be loss-averse.

The shape of the value function, on the other hand, holds that the desire to avoid losses drives consumers to treat the risk of experiencing a loss differently than obtaining a positive return. In the gain domain, the value function implies that a person will be averse to gambles involving positive outcomes, while in the loss domain an individual is assumed to be risk-taking when it comes to uncertain losses.

The weighting function

To explain consumer interest in purchasing insurance, we turn to the use of the weighting function postulated by prospect theory to characterize how individuals perceive probabilities. Empirical studies suggest that individuals overweight the chances of low-probability events where the likelihood is below 30–40 percent—risks that are most relevant to insurance—and underweight the chances of higher probability events occurring (Camerer and Ho 1994, Wu and Gonzalez 1996). According to prospect theory, highly unlikely events are either ignored or overweighted. Hence, the discontinuity of the weighting function is near zero.

For a low-probability event that is not ignored, a person who is risk-taking in the loss domain may still be willing to purchase insurance if his decision weight implied by the weighting function reflects an overestimation of the probability of a loss. In other words, a high enough perceived chance of incurring a loss makes insurance attractive, even with premiums that reflect a 30–40 percent

premium loading factor. This explanation has some intuitive psychological plausibility: some people worry (sometimes excessively) about low-probability, high-negative-impact events, and hence assign them high weights when considering their likelihood.

But there is a fundamental empirical difficulty with prospect theory's account of insurance purchase using decision weights that also applies to the expected utility model. Empirical research suggests that the loss probability often does not play a role in people's decision processes (Camerer and Kunreuther 1989, Hogarth and Kunreuther 1995, Huber et al. 1997). When loss probability is in fact considered, it is derived from experience, not from actuarial tables. Ralph Hertwig and his colleagues showed that when the probabilities are based on experience rather than on statistical summaries, people underweight low probabilities in making risky decisions except when there has been a very recent occurrence of the event class in question (Hertwig et al. 2004).

Preference for low deductibles and rebates

One of the best examples of how prospect theory can explain actual insurance behavior better than the benchmark model of demand is the choice of low deductibles and the purchase of insurance policies that offer rebates if one doesn't suffer a loss, even though such policies are generally not as financially attractive as those without such dividends.

The negative value of the additional premium caused by eliminating the deductible is very small relative to the very large reduction in the negative value caused by reducing the deductible to zero. A better inducement than a deductible to get critical infrastructure owners to avoid making claims would be to offer them a rebate from which claims are deducted. Conceptually, insurance with a rebate should be more attractive than an equivalent and less expensive policy with a deductible, since the negative value of the deductible is much greater than the positive value of the rebate even if one did not have any claims on the policy and thus was able to collect the entire rebate. Insurance policies with rebates may satisfy a firm's need to collect something on its insurance policy when it has not suffered a loss.

3.3. A Goal-based Model of Choice

Both expected utility theory and prospect theory assume that financial considerations determine a person's decisions regarding insurance purchase. But managers in a firm often construct or select insurance plans designed to achieve multiple goals, not all of which are purely financial (Krantz and Kunreuther 2007). The relative importance of these goals varies with the decision maker as well as the context in which the decision to purchase insurance may be triggered. For example, an insurance purchaser may think chiefly about the goals of satisfying the requirements of the bank that holds one of the mortgage loans. But when that same manager reflects the possible litigation against its board of directors, she may think chiefly about reducing anxiety and avoiding regret, and thus purchase the maximum insurance limit possible on that other insurance product.

To illustrate how the plan/goal representation captures the insurance decision-making process, consider behavior that is often observed: many purchase disaster insurance after suffering damage from one, but then cancel their policies when several consecutive years pass with no flood. One explanation is that avoiding anxiety and feeling justified are both important goals. Following disaster damages, anxiety is high, and reducing it is a salient goal; it is also easy to justify buying the insurance because a catastrophe has just occurred and the experience is deeply etched in the purchaser's recent memory. But a couple of years later, many people may find that the prospect of another such disaster no longer intrudes on their peace of mind, so anxiety avoidance takes on less importance.

3.4. Underinsurance against Catastrophe Losses

Many firms are more interested in buying insurance coverage after a disaster occurs, rather than prior to the event. This is true even though premiums are usually increase after a catastrophe. A recent study by the Office of the Mayor of New York City reveals that 92 percent of small and medium enterprises located in areas inundated by Superstorm Sandy in 2012 lack flood insurance (NYC 2013). And while more firms have purchased terrorism insurance today than was the case right after 9/11 when insurance was scarce and expensive, still about a third of large corporations lack this coverage. A recent report by the large insurance broker Marsh reveals that 30 percent and 37 percent of the firms they surveyed in the utility and transportation sectors, respectively, had no terrorism insurance under the federally-back terrorism risk insurance program (Marsh 2016).

Managers in firms may also want to purchase more insurance as a form of consolation should the firm suffer a loss. With respect to negative feelings about a situation, experimental findings indicate that people focus on the severity on an outcome will be rather than on its probability when they have strong emotional feelings attached to the event (Rottenstreich and Hsee 2001, Sunstein 2003). In the case of terrorism, a national field survey conducted in November 2001 revealed that Americans living within 100 miles of the World Trade Center felt a greater personal risk from terror than if they lived farther away (Fischhoff et al. 2003). This may explain the large New York area demand for terrorism insurance coverage immediately after 9/11 even at extremely high premiums (U.S. Government Accountability Office 2002 and Wharton Risk Management Center 2005) and that demand for that type of insurance products among firms located in that state remains one of the highest in the country still in 2016 (Marsh 2016).

Capital markets emerged in the 1990s to complement insurance and reinsurance in covering large losses from natural disasters through new financial instruments, such as catastrophe bonds industry loss warranties, sidecar reinsurers, and contingent loans see Kunreuther and Michel-Kerjan, 2011 for more details, and Cummins and Weiss 2009 for a technical review).

4.1 Features of a Catastrophe Bond

We will focus on catastrophe bonds here. To illustrate how cat bonds work, consider a firm or authority in the transportation sector, *SafeCompany*, who would like to cover part of its exposure against catastrophic losses. In order to do so, it creates a new company, *BigCat,* whose only purpose is to cover *SafeCompany.* In that sense, *BigCat* is a single purpose insurer (also called "special purpose vehicle, SPV"). When the contract is signed, the sponsor (*SafeCompany*) pays premiums to *BigCat.* On the other side, institutional investors –for instance a pension fund, a bank, a hedge fund, an insurer--who place their funds with the SPV *BigCat*; these funds constitute the initial principal for the bond to be issued by *BigCat.* Insurance premiums collected from *SafeCompany* will be used to provide the investors with a high enough interest rate to compensate for a possible loss should a disaster occur.

Suppose the losses from a disaster covered by the cat bond exceed a pre-specified trigger, for instance a named hurricane of category 2 of higher. Then the interest on the bond, the principal, or both, are forgiven, depending on the specifications of the issued catastrophe bond. These funds are then provided to *SafeCompany* to help cover its claims from the event. In addition to the interest rate on the cat bond, there are at least four other components for the investor to consider: the protection of the principal, the nature of the trigger, the size of the bond and the maturity of the bond.

Protection of the Principal

The principal of a catastrophe bond often consists of different tranches, which might or might not be protected. A *protected tranche* guarantees that the investor will receive the principal from this tranche when the bond matures. For this tranche, if a covered event occurs, the SPV stops paying interest and can extend the maturity of the loan for several years. An *unprotected tranche* has both principal and interest at risk should a covered event occur.

Trigger

The nature of the trigger varies from one bond to another. The trigger can be *indemnity-based*, meaning that the transaction is based on the actual losses of the sponsor. This eliminates the basis risk for the sponsor (the covered loss does not necessarily correlate perfectly with the amount of claim collected from the contract), but also reduces the transparency of the transaction for the investors. The trigger can also be based on industry losses using a predetermined *industry index of*

losses (e.g., the index is calculated by the Property Claim Services – "PCS" in the United States). The trigger can also be determined by a *parametric index*, such as an earthquake of magnitude 7 or greater on the Richter scale occurring in the San Francisco Bay area, or a Category 3 hurricane in New York City. A parametric index provides transparency for the investors, but sponsors may have significant basis risk.

Size of the Bond

The size of the bonds issued has increased over time. For example, of the five bonds that were issued in 1997, only one had capitalization higher than $200 million; in 2000 there were two such bonds, and in 2005 there were four (out of a total of ten). Likewise, there were two bonds with capital lower than $50 million in 1997 (out of a total of five), but none of the 43 new bonds issued between 2003 and 2006 had capital lower than $50 million (Guy Carpenter 2007). The transaction costs associated with the complex execution of these instruments (compared to traditional reinsurance) contributes to this trend toward larger bonds. Because cat bonds are uniquely designed transaction the size of the bond is in fact an agreement between the issuer and investors.

Maturity of the Bond

  The maturity of a bond is the period during which the SPV will cover *SafeCompany*. One advantage of cat bonds over traditional one-year (re)insurance contracts is that they can typically offer longer term coverage at fixed price– one to five years. Over time, the proportion of cat bonds with longer maturity has increased, an indication that these instruments are gaining trust within the reinsurance/finance community. While there is no standard as to how long the maturity of a cat bond should be it is fairly common to see three-year cat bonds.

In the context of highly volatile (re)insurance prices that often occur after large catastrophes, cat bonds offer an important element of stability for those who use them by guaranteeing a pre-defined price over several years, assuming that the entire capital of the bond is not triggered (in which case a new bond has to be issued under price conditions that are likely to differ). We believe that this stability has been largely undervalued so far.


4.2 Why Catastrophe Bonds Are Attractive Instruments

Several forces combined to make these new instruments attractive. The shortage of reinsurance following Hurricane Andrew in 1992 and the Northridge earthquake in 1994 led to higher reinsurance prices and made it feasible for insurers to offer catastrophe bonds with high enough interest rates to attract capital from investors. In addition, the prospect of an investment that is uncorrelated with the stock market or general economic conditions is also attractive to capital market investors. Finally, catastrophe models emerged as a tool to more rigorously estimate loss probabilities, so that disaster risk could be more accurately quantified and priced than in the past.

Following Hurricane Katrina, there has been a significant increase in the number and volume of catastrophe bond issuances and the creation of sidecars, but the total volume of financial protection had long remained somewhat limited compared to what is currently provided by traditional reinsurance. While at the beginning of this new market, most insurers were actually insurers seeking alternative reinsurance options, in recent years, several non-insurer organizations (ranging from Disney, Universal Studios, Electricity de France, Dominion, Metropolitan Transit Authority) and governments (Thailand, Mexico, and more recently several states in the U.S. as well as public disaster programs including the California Earthquake Authority) are using these tools to hedge some of their exposure to disasters (Michel-Kerjan et al. 2011).

More transactions could mean a more liquid market, which in turn will attract more sponsors and investors, providing the much needed capital to finance future catastrophes. And indeed this market has been continuously growing in recent years, largely driven by institutional investors (e.g. pension funds) seeing these instruments as a new class of assets. In all, there was $26bn outstanding capital in the cat bond market in 2016 alone, compared to only $2.8 billion in 2000. Figure 4.1 below depicts the evolution of capital outstanding over time and shows the significant increase that happened over the years2.

Figure 4.1. Catastrophe Bonds Capital Outstanding – 2000-2016 (in $ Billion)
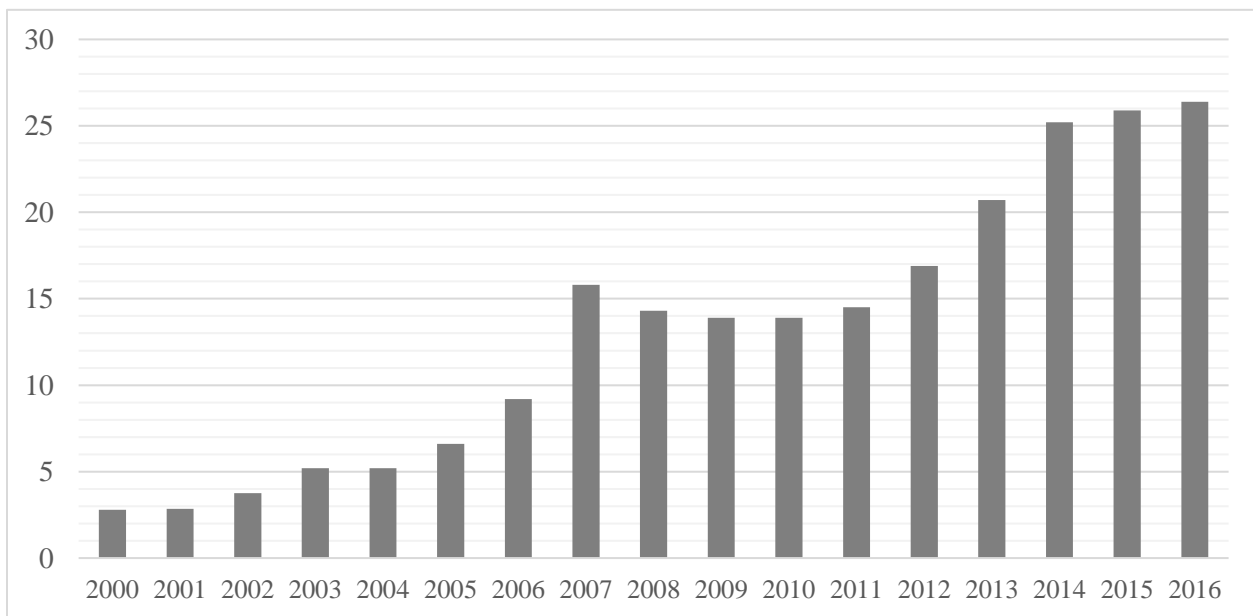
Sources: Authors with data from Artemis.

While catastrophe bonds will not fully replace more traditional insurance and reinsurance, they certainly constitute an important complementary alternative to it. The emergence of this new market has also forced traditional insurers and reinsurance to be more competitive. The Metropolitan

---

2 The capital outstanding in this figure also includes other insurance-linked securities risk.

Transit Authority (MTA) is one example of an infrastructure organization that chose a catastrophe bond to address their risk management needs, as described in the text box below.

In 2015, Amtrak also used a similar risk transfer instrument to purchase $275 million of reinsurance protection from the capital markets for its wholly owned captive. The PennUnion Recat bond covers storm surge, wind and earthquake perils. Storm surge water height measurements are captured at seven tidal gauge stations in the Long Island Sound, East River, Lower New York Bay and Delaware River. Wind measurements are compiled for 60 ZIP codes along Amtrak's Northeast Corridor railways from Washington, D.C. to near Providence, Rhode Island. Earthquake intensity measured for 21 ZIP codes within the states of Delaware, New Jersey, New York, Pennsylvania and Rhode Island (Insurance Journal, 2015).

Metropolitan Transit Authority (MTA)'s First Catastrophe Bond

According to information collected by Artemis, a dedicated information database, "In 2013 MetroCat Re Ltd., a Bermuda domiciled special purpose insurer established for issuing series of catastrophe bond notes, has been set up to support the risk transfer needs of First Mutual Transportation Assurance Co. (FMTAC), the New York State-licensed captive insurer and subsidiary of the New York Metropolitan Transportation Authority (MTA). This transaction provides cover just for storm surge, resulting from named storms. FMTAC will receive from the cat bond a three-year source of per-occurrence reinsurance protection for $200 million against storm surge measured during named storm events on a parametric trigger basis.

The MTA's motivation for issuing this three-year maturity cat bond is to expand and diversify its sources of reinsurance protection and also to obtain some coverage on a parametric basis, which should payout more quickly than traditional insurance coverage.

The transaction features a parametric trigger based on actual recorded storm surge heights from a number of zones around New York City. A loss payment would be due based upon a parametric event index meeting or exceeding a trigger level for an applicable area, meaning that it may not necessarily directly correlate with the losses of the sponsor. The notes offer protection against named storms that generate a storm surge event index that equals or exceeds 8.5 feet for Area A or 15.5 feet for Area B. Area A includes tidal gauges located in The Battery, Sandy Hook and Rockaway Inlet, while Area B includes tidal gauges in East Creak and Kings Point. A trigger event occurs when either Area's event index calculated by RMS equals or exceeds the respective trigger levels. If a trigger event occurs, the loss payment from MetroCat to FMTAC will be 100% of the outstanding principal amount, so there is no sliding scale of loss here. Under Superstorm Sandy these were the two areas that received the most flooding that entered subway and transit tunnels.

The cat bond only covers storm surge from named storms, which must be tropical cyclones, tropical storm or hurricanes at some point in their lifespan. Extra-tropical cyclones are excluded, which means large storms forming in the northern Atlantic, such as the Great Nor'Easter of 1992, would not be covered.

Risk Management Solutions (RMS), whose risk models are used for this cat bond, said that no non-hurricanes have ever caused storm surge levels that would have breached the parametric trigger. Based on their historical modeling analysis, there have been two hurricanes which would have breached the trigger level. Hurricane Donna (1960) generated a modeled storm surge height of 9.52 feet in Area A and Superstorm Sandy (2012) generated a modeled storm surge height of 10.93 feet in Area A. Both of these storms would have exceeded the MetroCat Re Area A trigger level.

Storm surge data is collected from the National Oceanic and Atmospheric Administration (NOAA) for the tidal gauges at the Battery, Sandy Hook and Kings Point locations, and from the United States Geological Survey (USGS) for the Rockaway Inlet and East Creek tidal gauges." (Taken from Artemis.bm)

The value of the services provided by infrastructure leads to significant economic, social, and environmental impacts when disruptions occur (Wilbanks et al. 2012). Loss of infrastructure can lead to diminished quality of life or additional costs at the household level (Kousky 2014). The resilience of cities after a disaster is largely determined by the functioning of complex infrastructure systems with interdependence (Chang et al. 2014). Funding delays for restoration of infrastructure are particularly costly due to interdependencies (Kunreuther and Michel-Kerjan 2013).

There are three key components to managing extreme events: risk assessment and identification, mitigation and adaptation, and transfer of risks that cannot be eliminated or reduced (Courbage and Stahel 2012). As we discussed earlier in this report, the insurance industry plays a role in each of these three components. This section describes the infrastructure resiliency gap and its costs (section 5.1), challenges and barriers to resolving the gap (section 5.2) and then discusses two critical infrastructure sectors for which resilience is key to community recovery after a disaster: Power (section 5.3) and Transit/Rail Power (section 5.4). Some of the infrastructure successes and failures that occurred as a result of Superstorm Sandy are discussed in section 5.5.

5.1. The Nature of the Infrastructure Resiliency Problem and its Costs

There is a gap between the preparedness of critical infrastructure and actual risk (Urlainis et al. 2014). Urlainis et al (2014) notes high vulnerability of critical infrastructure and a mismatch between the actual risk and the investments made by decision-makers for preparedness. Infrastructure risks are greatest for systems located in areas prone to extreme events, limate-sensitive environmental features, or stressed by age or demand (Wilbanks et al. 2012). In the United States, infrastructure is generally becoming less resilient due to decay and deterioration, due to poor maintenance and delays in replacement PwC 2016). Infrastructure resiliency improvements tend to be implemented during restoration efforts when funds are available and the perceived need for resiliency is high, or when a construction project is underway for other reasons. Resilient recovery after a disaster can be encouraged through a combination of regulation and both financial and non-financial incentives. Codes and standards for infrastructure should be designed to encourage resiliency throughout the design, build, and operation stages, and continually updated to address current and future hazard conditions. Thinking about homeland security and climate change can also encourage resiliency improvements (PwC 2016).

The majority of federal disaster assistance funding is spent on repairing public infrastructure (Pidot 2007), so clearly there is a huge economic reason for improving infrastructure resilience. Furthermore, even private operators rely on public infrastructure in the interdependent nexus of infrastructure systems, and disruptions in public infrastructure systems can cause significant impacts to dependent systems.

Resilience improvements must compete with other infrastructure investments for funding (Brashear 2011). Different infrastructure systems are managed at different regional scales (NIST 2016), which further complicates community disaster recovery and resiliency. Public-private partnerships may be helpful in generating resiliency improvements, Furthermore, 85 percent of the critical infrastructure in the United States is privately owned, so the private sector clearly has a role in improving resiliency in these systems. Private sector infrastructure owners need to know that there is a financial return associated with improving resilience, and will not make resiliency improvements that don't fit within their business model. Even in the recovery phase, private infrastructure managers may choose to forego resiliency improvements if they are cost-prohibitive. (PwC 2016).

There are various government and utility approaches to increasing infrastructure resilience. Short- and long-term measures to protect infrastructure could be funded, mandated, or partially subsidized by local, state, or federal government (McGovern 2011). Policymakers can and must take a leadership role to reduce risks through building codes and development decisions. They can also unlock barriers to increasing resilience of industry (Entergy 2016). The methods used by utilities to lessen the financial impact of disaster restoration are inconsistent between different utilities (DOE 2013). In some cases, it is rate-payer funded cost recovery, sometimes with short-term borrowing. Some utilities self-insure for major storms or purchase short-term catastrophe insurance (DOE 2013). In the US, applicant or facility receiving disaster assistance must commit to obtaining and maintaining insurance to protect against future damage (US DHS 2011).

A report by the American Society of Mechanical Engineers (ASME) Innovative Technologies Institute (Brashear 2011) provides an "objective business process for identifying and evaluating ways that metropolitan regions can enhance their security and resilience." It details a process called regional Resilience/ Security Analysis Process (RR/SAP) for evaluation of security and resiliency improvements. The process appears to be useful in identifying and evaluating resiliency improvements, as well as increasing the true value of investment in new and renewed infrastructure. However, the report does not specifically address incentives and funding sources but does note that some utility companies and other corporations involved with infrastructure now use Enterprise Risk Management for budgeting, and that resiliency improvements need to fit into this process.

A recent study by the consulting firm PwC (PwC 2016) provides the following six key guidelines for infrastructure resilience:
- Focus on preparedness, prevention, and mitigation now
- Foster collaboration across public and private sectors
- Motivate communitywide engagements
- Coordinate across regional boundaries
- Encourage resilient recovery with optimal incentives
- Build back stronger and smarter

The study notes that the Institute for Business and Home Safety in the U.S. is developing a certification for resiliency, with the objective of securing tax credits for those that comply with the standards they are establishing. Rating buildings for resilience will raise awareness and interest in resiliency.

Infrastructure providers have limited financial incentive to be concerned with the effects of disruptions in their system on those dependent on infrastructure. In this regard there is no governance that addresses issues of infrastructure interdependencies and implications for regional resilience (Chang et al. 2014). Infrastructure organizations generally are much more aware of "upstream" infrastructure than "downstream" infrastructure (Chang et al. 2014). Private infrastructure providers are accountable to shareholders, so minimizing investment and repairs costs while maintaining the organization's reputation is generally their goal. In the case of power outages, dependent systems are generally liable for their own losses so the electricity provider doesn't necessarily consider societal benefits in their decision-making (Chang et al. 2014).

This report highlights a few of the published studies and guidance on infrastructure resiliency that are available. While useful, these resources do not focus on the financial aspects of infrastructure resilience as well as the barriers to increasing resiliency. In this regard NIST published a guide in 2016 for communities to incorporate short- and long-term measures to enhance resilience and focus on planning for recovery (NIST 2016). While report provides insight into infrastructure resiliency improvements, there is little mention of funding these improvements, and the barriers for doing this.

5.2 Challenges and Barriers to Improving the Infrastructure Resiliency Gap

Governments often act as the insurer of last resort, which raises questions about effectiveness of pricing and sharing risks through the insurance market (King et al. 2013, Pidot 2007). As described in Section 1.3, the role of the federal government in disaster relief has been steadily expanding. The primary mechanism under which the federal government provides disaster relief funds is the Stafford Act. Stafford Act funding can deter infrastructure resiliency in two ways. First, infrastructure managers may rely upon Stafford Act funding in lieu of preventative measures or insurance to sustain their system under the occurrence of a disaster. Second, Stafford Act funding only applies to the replacement of a damaged part of an infrastructure system, and does not cover the cost of improving resiliency in a system. Resiliency improvements can be made using additional funding sources, but may not occur if these funds are not available.

Other sources of substantial federal funding are also available to assist infrastructure systems in some disasters. Figure 5.1 shows the distribution of all federal funding sources for Superstorm Sandy. Funding came from FEMA, Housing and Urban Development (HUD), the Department of Defense (DOD), the Department of Transportation (DOT), and other Federal agencies (Barletta, 2016). Federal Agency involvement outside of FEMA and HUD generally depends on the extent of

the disaster and the affected entities. For instance, the Department of Transportation will be involved when the disaster significantly impacts transportation infrastructure. (See Section 6 for more discussion on this topic.) Some of these sources of federal support require a disaster declaration under the Stafford Act, while others do not. Sources of federal funding also differ in whether or not they can be used for resiliency improvements or solely for restoration.

Figure 5.1 Distribution of Federal Disaster Relief Funds for Superstorm Sandy
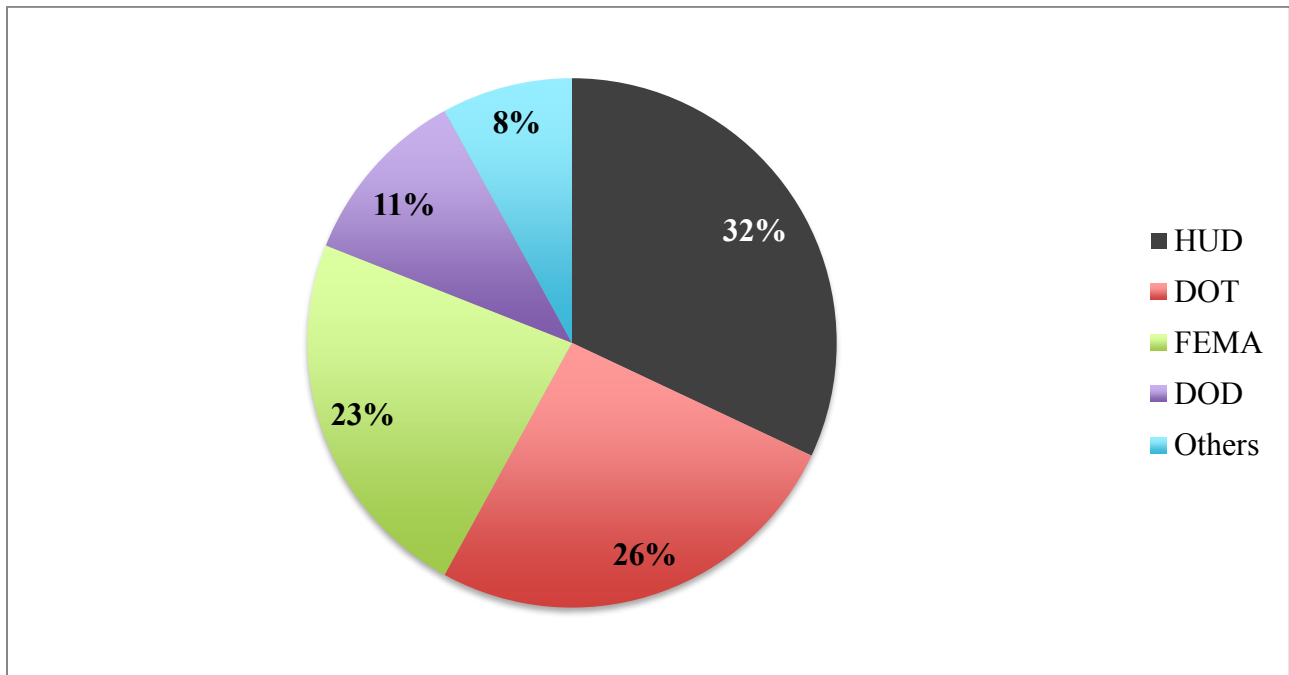
In addition to the disincentives for investing in insurance and risk reducing measures posed by federal disaster relief, other challenges also inhibit resiliency in infrastructure systems. Due to security concerns, critical infrastructure organizations generally do not share information about system vulnerabilities that could be helpful for preparedness planning (Chang et al. 2014). Another challenge is that infrastructure managers often do not have direct experience with major disasters. Unless they learn from disasters in other regions and infrastructure systems, they may not have a clear understanding of the vulnerability in their system and the need for resiliency (Chang et al. 2014). These challenges lead to underinvestment in resiliency improvements for individual infrastructure systems. An individual infrastructure system manager cannot be expected to overcome these challenges without incentives (Chang et al. 2014).

A report by the Geneva Association (Courbage and Stahel 2012) highlights two key challenges in increasing infrastructure resilience: 1) government relief can deter preventative/ ex ante action (as we discussed above), and 2) politically, it is more difficult to induce costly protective measures ex ante than to provide assistance after a disaster (Courbage and Stahel 2012). A report by the Council of the Organization for Economic Cooperation and Development, which represents 34 of the richest

countries in the world, (OECD 2010) acknowledges that the costs associated with disasters need to be assessed and financially managed before a major loss occurs. This requires the government and private sectors to work together (OECD 2010). Perhaps with the assessment prior to a disaster, the role of government and the private sector could be clearly delineated so that each bears the appropriate financial burden of a disaster, even though we recognize this might be hard to do comprehensively. But governments could quantify the costs that they would bear under current programs, as well as under the implementation of new strategies (Courbage and Stahel 2012).

Some barriers to improving infrastructure resilience are:
- State-aid after a disaster
- Political challenge of requiring ex ante improvements
- Lack of information sharing due to security and vulnerability concerns
- Infrequency of events lowers perceived urgency
- Insufficiency in funding for infrastructure maintenance and improvements

While the barriers to enhanced resiliency in critical infrastructure systems are significant, strategies for incentivizing resiliency that can work are noted by the NIBS study (2015):
- Carrot-and-stick measures
- Implementing incentives and requirements that are supported by data
- Tailoring programs to different states
- Creating exceptions to state-wide code requirements for special circumstances

In light of these barriers and challenges, along with the significant opportunity for improvement, a set of twenty key measures to enhance resiliency through insurance and other incentives is presented in section 6.

Power and Transit/Rail are two critical infrastructure sectors for which resilience is key to community recovery after a disaster. These two sectors were chosen for further analysis and discussion due to their importance to communities and their interdependencies with other infrastructure systems. They also have differing operational and structural components. These two systems were discussed with representatives from large insurers and insurance brokers as part of our ongoing research with CIRI and DHS and are highlighted in Sections 5.4 and 5.5.

5.3 Power Infrastructure

Risks and Resiliency

U.S. power systems face threats from natural hazards along with emerging threats involving cyber-security and space weather (DOE 2013). Energy systems include generation, distribution, and transmission components, and 90% of all power outages occur along transmission lines (US DOE 2010). Many other utilities are dependent on electricity (hospitals, water systems, transportation,

telecommunications) (DOE 2013), leading to widespread ancillary impacts of power outages. US energy systems were given an ASCE report card grade of D+ in 2013. These systems suffer from aging equipment and weather-related events were the main causes of outages in the US between 2007-2013 (ASCE 2013). Additional volatility in reliability is associated with renewable energy (Bruch 2011).

Common measures for improving resiliency include pole inspection and maintenance, vegetation management, and mobile transformers and substations for temporary replacement of damaged assets. Other pre-disaster measures include updating hurricane plans and training staff, securing fuel prior to a storm for post-storm recovery, and securing exemptions from evacuation orders to speed up restoration (US DOE 2010). Utilities rely on mutual assistance groups as a means of resiliency for storm recovery (US DOE 2010).

A report by Entergy (2016) specifies resiliency measures for the oil and gas industry including improving standards for offshore platforms, replacing semi-subs with drill ships, constructing levees for refineries and petrochemical plants. The report also recommends improving the resilience of electric utility systems, and improved building codes. Suggested community measures include beach nourishment, wetlands restoration, and levee systems. These measures should be funded by a combination of public and private funds (Entergy 2016). There is no regulation of storm hardening for refineries and pipelines, only industry standards and best practices (US DOE 2010).

While many other types of infrastructure dependent on energy systems, so is the energy system dependent on others. For instance, power generation facilities are dependent on rail networks for coal/fuel shipments. The rail network is not as redundant as roads, and disruptions have a significant impact (NIST 2016).

Insurance and Incentives for Resiliency

Most power utilities have sophisticated risk transfer mechanisms in place. The cost of insurance is generally embedded in their electricity rates. Resiliency improvements don't necessarily play a part in insurance pricing for power utilities; rather, utilities are more likely to see increased rates or denial of coverage if they fail to mitigate risk to an acceptable level.

Electricity producers usually buy property damage and business interruption insurance. Distributors generally have the same option for business interruption; however, property damage coverage is limited due to the heavy exposure of transmission and distribution lines (Bruch 2011). New insurance products for energy companies offer financial income protection for adverse weather events (like warm winters) (Bruch et al, 2011). Special business interruption insurance for financial loss associated with data malfunctions (operator error, hackers, data malware) is available (Bruch 2011). Cyber risks are becoming one of the biggest insurance issues for power utilities, both in terms of privacy and property damage. Power companies generally purchase only physical damage

insurance, not business interruption insurance, because the insurance industry is reluctant to provide it. The generating sectors of utilities usually have reserve generating facilities and the potential exposure is significant. Utilities don't buy coverage on the transmission and distribution lines (the grid), because the whole network has huge exposure to storm damage.

Insurance coverage for loss of power may also be sought by dependent infrastructure systems and other organizations. For power systems, dependent service providers are liable for consequent losses (Chang et al. 2014). For blackouts, risk transfer via insurance usually requires a physical damage claim to trigger a business interruption claim (Bruch 2011, DOE 2013).

Improvements to resiliency in energy systems often occur in response to government intervention. Public utility commissions issue rules and regulations pertaining to hardening and can authorize the inclusion of hardening and resiliency costs in a utility's base rate. Since 2005, multiple state public utility commissions have issued rules and/or regulations pertaining to electricity infrastructure hardening. Many hardening and resiliency initiatives by utilities were undertaken in response to these regulations (US DOE 2010). The Florida Public Service Commission (FPSC) has monthly reporting requirements, and authorized research, rules, and guidance following the 2004-2005 hurricanes (US DOE 2010). The Louisiana Public Service Commission (LPSC) released 3 dockets on infrastructure hardening. The Public Utility Commission of Texas (PUCT) research 8 rules on storm hardening (US DOE 2010).

The National Association of State Energy Officials (NASEO) in conjunction with state and territory energy offices has led resiliency efforts for the energy sector. These efforts include training and implementation for building energy codes, rebate and discount programs, industry partnerships with homebuilders, contractors, and big box stores, energy assurance planning, and identification of state level opportunities to specifically integrate disaster resilience and mitigation into existing energy programs (NIBS 2015).

One means of improving energy system resiliency is through micro-grids, which provide for distributed energy resources. They can ensure power continuously during a disruptive event. Micro-grids can be installed as a segment of the utility's grid or separately at a customer's facility and are one solution for critical facilities (NIST 2016). Insurance providers could potentially provide reductions in business interruption premiums for infrastructure systems that install back-up or distributed energy resources to reduce down-time during a disaster that impacts power supply.

5.4 Transit/Rail Infrastructure

Risks and resiliency

It has been estimated that U.S. transit systems have a $25 billion per year funding deficiency and are given were given an ASCE infrastructure report card grade of D in 2013 (ASCE 2013). A recent OECD report (2016) indicates that transportation infrastructure has been the source of a very high percentage of public sector infrastructure damages during recent disasters.

The rail industry consists of two markets: freight and passenger. The primary risk focus in the freight market is HAZMAT, whereas terrorism and quality of rail equipment are key focuses in the passenger industry. Many rail entities are experiencing issues associated with deferred maintenance and both redundancy and replacement issues are observed in the rail industry.

There are a variety of sources of potential federal disaster recovery funds for transportation infrastructure. Some of these require a federal disaster declaration under the Stafford Act, and some do not. In some cases, disaster relief funding is made available through a specific Congressional appropriation following a disaster. Some involve administration and oversight by FEMA, and others are solely under the purveyance of other Federal agencies. In addition to FEMA, HUD, SBA, and Department of Commerce Economic Development Administration (EDA) funding, some transportation-specific disaster relief funding sources are as follows:

- Federal Highway Administration (FHWA) Federal-aid Highway Emergency Relief Program
- Federal Transit Administration (FTA)
- Federal Railroad Administration (FRA)
- Federal Aviation Administration (FAA)

Insurance and incentives for resiliency

The US DOT Federal Transit Administration (FTA) Emergency Relief Program (ERP) helps states and public transportation systems pay for protecting, repairing, or replacing equipment and facility damage because of emergencies, including natural disasters (U.S. House of Reps. 2015). This program was founded under the Moving Ahead for Progress in the 21st Century (MAP-21) Act, which pertains to federal surface transportation. The Emergency Relief Program is intended to improve coordination between the US DOT and DHS to expedite assistance to public transit providers (US House of Reps 2015). Projects that are eligible for emergency relief funding include emergency operations, emergency protective measures, emergency repairs, permanent repairs, resilience projects, and spare parts. Transit facilities such as buildings (including maintenance and storage facilities and above-ground stations and terminals) located within special flood hazard areas (SFHAs) must be insured against flood damage. Flood insurance is not required for underground subway stations, track, tunnels, ferry docks, or for any transit facilities situated outside of an SFHA.

For uninsured buildings in the SFHA that have previously received federal funding, FTA will only provide assistance after the maximum limit of coverage made available under the NFIP, or the amount of prior Federal funding, whichever is less, is subtracted from the total restoration cost. FTA grant recipients are required to obtain and maintain flood insurance on buildings and contents for which FTA has provided emergency relief funds. FTA disaster relief resources are separate from FEMA's. The Disaster Relief Appropriations Act of 2013 provided $10.9 billion to the ERP for Hurricane Sandy recovery and relief.

Transit organizations seek private insurance for catastrophe risks. The Metropolitan Transit Authority (MTA) paid a high price for post-Sandy natural hazard coverage (Kunreuther and Michel-Kerjan 2013). Insurance coverage for rail companies is generally dictated by the class and size of the railway, and sometimes by local laws. Insurance is generally first party coverage on an all-risk, replacement cost basis. The primary and layered approach to insurance for rail causes a high potential for non-concurrency. Among the leaders in the insurance industry are The Lexington (AIG), Lloyds London Marketplace, and the continental European market (Allianz, Zurich, Munich Re, SwissRe, Scor, etc.).

Some market leaders we have interviewed also pointed to some issues that the insured have had with their insurers. For instance, the amount of coverage that insured entities received during Sandy was dependent on how the policy was written, and whether the hazard was attributed to flooding versus storm surge. Flood coverage typically has an aggregate limit, whereas storm surge does not. This might have been confusing to several organizations when they took a much closer look at their insurance policy *after* the disaster than they had done before. Some entities are still negotiating settlements from Sandy. For some of them, the replacement process after a disaster has been lengthy and it can take a long time to recover a loss. From our interviewed we learned that, more recently, the combative claim policy exhibited by insurers has lowered the appetite for insurance for some transit systems and is calling into account the efficacy of insurance coverage. This was true following Sandy.

The link with risk reduction is not as strong as it could be as insurers do not demand that their clients take steps to mitigate risk along the rail. That said, the level of risk mitigation demonstrated by a client in the insurance submission document is used to prove that the company is a good risk; a condition of insurability we discussed in section 2 of the report.

5.5 The Metropolitan Transit Authority (MTA): Insurance and Government Relief

Superstorm Sandy provides a vivid example of disruptions and costs to taxpayers associated with lack of resiliency in infrastructure systems. Of the over $50 billion in funds allocated by Congress to fund recovery efforts for Superstorm Sandy, more than $13 billion was earmarked for projects in New York City (NYC Sandy Funding Tracker 2016). Much of this funding is associated with

infrastructure systems, and transportation infrastructure systems in particular. Federal funding was allocated by multiple federal agencies, including the Federal Emergency Management Agency (FEMA), Housing and Urban Development (HUD), the Federal Highway Administration, the Federal Transit Administration, and the US Department of Labor (NYC Sandy Funding Tracker 2016). Initial funding amounts were set in 2013, with additional funding allocated subsequently.

The Metropolitan Transit Authority (MTA) of New York suffered over $5 billion in damages during Sandy, including damage to rail and subway systems, tunnels, stations, and equipment. The MTA is a public benefit corporation responsible for public transportation. As shown in Figure 5.2, the MTA's insurance paid out about $1 billion for Superstorm Sandy. The MTA received another $4.2 billion in relief from the Federal Transit Authority (FTA). This $4.2 billion included $898 million for resiliency improvements. The MTA also received $3.7 million from FEMA for immediate repairs (e.g. washed out tracks and damaged signals, power and communication lines, and stations).
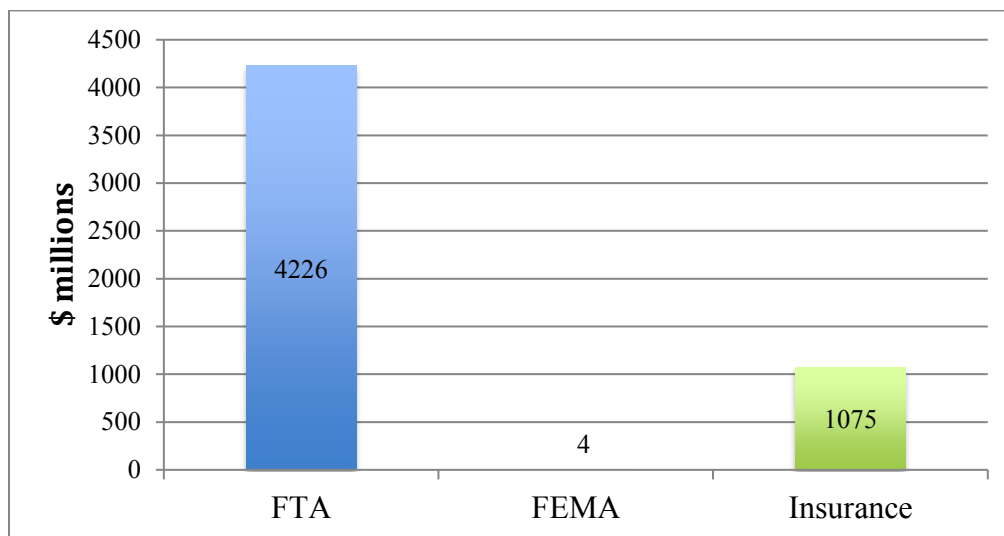

Figure 5.2 Amounts Received by the MTA from Private Insurance, FEMA and FTA (government relief and recovery) for Superstorm Sandy

The MTA established a Sandy Recovery and Resiliency Division with one goal being to protect all points where the subway system could be flooded in a future storm (MTA 2016). As noted previously, the MTA also transferred more of its risk to the financial markets by issuing a catastrophe bond to insure damage from potential future storm surge, as discussed in section 4.

The FTA spent $6.5 billion for Sandy recovery, $4.2 billion allocated to MTA and the remainder allocated to transit systems in Connecticut, Massachusetts, New Jersey, New York, Pennsylvania, and Rhode Island. FTA also allocated another $10 billion for improving specific transit resiliency projects in Connecticut, Washington D.C., Massachusetts, New Hampshire, New Jersey, New York,

and Pennsylvania. MTA was allocated $1.6 billion of this funding in support of 14 resiliency improvement projects3 (FTA 2016).

The tremendous expense to taxpayers along with the substantial business interruptions associated with Sandy highlight the need for improvements in infrastructure resiliency. These improvements may be achieved through financial/insurance mechanisms as well as regulatory mechanisms. In addition to the high cost of disaster relief associated with this disaster, there was a high cost on the insurance side. Total insured losses associated with Sandy were about $37 billion. Roughly $20 to $25 billion of this cost was on private insurance, with the rest falling under the federally run national flood insurance program (NFIP).

Affected states have reacted by making resilience a key priority and partnering with the private sector in that endeavor. The State of New Jersey, for instance, established a dedicated New Jersey Energy Resilience Bank (see box below). We believe such dedicated financing instruments can play a critical role moving forward.

New Jersey Energy Resilience Bank

Superstorm Sandy caused 8.1 million homes to lose power and $25 billion in lost business activity. In light of the disruption caused by the storm, the State of New Jersey ordered improvements to electric distribution companies storm planning and response, utility hardening and resilience investments, and developed a New Jersey Energy Resilience Bank (ERB). The ERB focuses on developing distributed energy resources to help keep critical facilities like wastewater treatment plans operational during future power outages (NJ website: Four Years After Sandy 2016). The ERB was the result of a collaboration between the New Jersey Board of Public Utilities (BPU) and the New Jersey Economic Development Authority (EDA) and was financed with $200 million from New Jersey's second Community Development Block Grant – Disaster Recovery (CDBG-DR) allocation. Project financing options through the ERB include both grants and loans. To qualify for this funding, an entity must have been impacted by Sandy or another qualifying disaster and much have sustained either physical damage or indirect damage that resulting in flooding or loss of power preventing the treatment of wastewater or drinking water.

---

3 The $1.6 billion in funding was allocated in support of the following projects: emergency communication enhancements ($75 million), flood mitigation in yards ($617 million), hardening of substations in flood prone areas and purchase of mobile substations ($112 million), protection of tunnel portals and internal tunnel sealing ($43 million), flood resiliency for Long Island City Yard ($19 million), flood resiliency for critical support facilities ($24 million), protection of street level openings in flood prone areas ($301 million), Metro-North Railroad power and signals improvements ($38 million), internal station hardening ($20 million), pumping capacity improvements ($24 million), right-of-way equipment hardening in flood-prone areas ($64 million), New York-New Jersey River to rail resiliency (R4) project ($81 million), Rockaway line protections ($137 million), flood resiliency for critical bus depots ($45 million) (FTA 2016).

Based on our interaction and interviews with leaders of the insurance and reinsurance industry, infrastructure owners and operators (Appendix A), along with findings from research activities we summarized so far, we now turn to a set of twenty proposals for DHS's consideration.

6.1 Improving Risk Assessment

Proposal #1: Develop modern risk assessment capability

Our research and interaction through interviews with large insurers, reinsurers, brokers and critical infrastructure (CI) owners reveal large differences in what is known about the risks CI face. Some know they have a flood problem but have not quantified the risk, focusing instead on flood event scenarios that have already occurred in the areas where they operate. Others have used catastrophe modeling to come up with a probabilistic distribution of a number of plausible scenarios of floods based on the latest science available.

Catastrophe models have been developed and improved over the past 25 years to more accurately assess the likelihood and damages associated with disasters of different magnitudes and intensities. Today, insurers and reinsurers utilize the estimates from these models to determine risk-based premiums and how much coverage to offer in hazard-prone areas (Grossi and Kunreuther 2005).

Work by our colleagues at the DHS's Critical Infrastructure Resilience Institute on cascading impacts of disasters and interdependencies across infrastructure systems is also critical because losses from disasters can both be direct and indirect. For example, a blackout will directly affect rail transportation and thus have an indirect effect on business interruption.

Senior management of these critical infrastructure organizations are more likely to agree to invest in resilience measures if the benefit/cost of the proposed measures can be calculated. This typically requires a probabilistic modeling approach. The advantage of developing more advanced risk assessment capability is also that it brings transparency in the discussion the CFO of the infrastructure system will have with the insurers.

6.2 Incorporating Choice Architecture

Proposal #2: Frame the risk differently to change behavior

Our research has shown the importance of incorporating behavioral considerations on both the supply and demand sides of insurance for protecting infrastructure. The term *choice architecture* indicates that people's decisions often depend in part on how different options are framed and presented (Thaler and Sunstein 2008). *Framing* in the context of LP-HC events typically refers to the way in which likelihoods and outcomes are characterized. One can also influence decisions by

varying the reference point or by changing the order in which alternatives and/or their attributes are presented, or by setting one option as the no-choice *default option* (Johnson et al. 2012).

Probability is more likely to be a consideration if it is presented using a longer time frame. People are more willing to wear seat belts if they are told they have a 1-in-3 chance of an accident over a 50-year lifetime of driving, rather than a 1-in-100,000 chance of an accident on each trip they take (Slovic, Fischhoff, and Lichtenstein 1978). Similarly, a homeowner or manager considering earthquake protection over the 25-year life of a home or factory is far more likely to take the risk seriously if told that the chance of at least one severe earthquake occurring during this time period is greater than 1-in-5, rather than 1-in-100 in any given year (Weinstein, Kolb, and Goldstein 1996). Studies have shown that even just multiplying the single-year risk so the numerator is larger — presenting it as 10-in-1,000 or 100-in-10,000 instead of 1-in-100 — makes it more likely that people will pay attention to the event (Slovic, Monahan, and MacGregor 2000).

People are better able to evaluate low-probability risks when these are presented via a familiar concrete context. For example, individuals might not understand what a one-in-a-million risk means but can more accurately interpret this figure when it is compared to the annual chance of dying in an automobile accident (1-in-6000) or lightning striking your home on your birthday (less than one-in-a-billion). Studies have also found that comparisons with familiar risks — rather than just specifying the probability of a loss or an insurance premium — are much more effective in helping decision makers assess the need for purchasing insurance (Kunreuther, Novemsky, and Kahneman 2001).

Proposal #3: Build credible worst-case scenarios

Another way to frame the risk so that decision-makers pay attention is to construct a worst-case scenario. Mangers of infrastructure facilities in hazard-prone areas who learn about the financial consequences of being uninsured if they were to suffer severe damage from a flood or earthquake would have an incentive to purchase insurance coverage and may refrain from canceling their insurance if they have not made a claim for a few years. One could then provide them with information on the likelihood of the event occurring over the next 25 years rather than just next year.

Default options are also important to consider. Field and controlled experiments in behavioral economics reveal that consumers are more likely to stick with the default option rather than opting out in favor of some other alternative. To date, this framing technique has been applied to situations where the outcome is either known with certainty or when the chosen option (such as a recommended 401(k) plan), has a higher expected return than the other options (Madrian and Shea 2001, Thaler and Benartzi 2004). It is not clear whether facilities that failed to purchase coverage would reverse course if having insurance against an extreme event were the default option, given the intuitive thinking that individuals employ for these types of risks. More empirical research is needed to more fully understand the role that default options can play with respect to encouraging insurance protection against extreme events in the context of infrastructure protection.

6.3 Insurance as an Incentive to Invest in Risk Reduction Measures

Proposal #4: Structure insurance premiums to reflect risk

Insurance premiums should be based on risk to provide infrastructure owners with accurate signals as to the nature of the hazards they face and to encourage them to engage in cost-effective mitigation measures to reduce their vulnerability. Risk-based premiums should also reflect the cost of capital that insurers need to integrate into their pricing to assure an adequate return to their investors.

Insurers and infrastructure owners would benefit from transparency in rate setting: What is the basis for the premiums insurers charge for protection against a given risk? Can it be communicated to owners so they appreciate the nature of the risk they face? What resilience and mitigation measures can insurers and infrastructure owners jointly identify that will significantly decrease insurance premium? Can managers in those organizations explore risk reduction measures with insurers in return for premium reductions or extended protection?

Proposal #5: Use insurance to incentivize resilience investments

Reduced insurance premiums for more resilient critical infrastructure. If insurance premiums truly reflect the risk faced by an infrastructure owner or operator, then insurance companies can offer reduced premiums for those that reduce property losses and business interruption claims.

Increased and broader insurance coverage to more resilient critical infrastructure. By demonstrating they have invested in resilience-improving measures, infrastructure owners are more likely to access more insurance coverage at a given price. If they can show that they are focusing on risk management strategies they are also more likely to find insurers willing to provide them with coverage. For example, insurers might be reluctant to insure against cyber attacks and data breaches if the critical infrastructure owner cannot demonstrate that proper protection measures are in place.

Providing information on risk management options for more resilient infrastructure. Insurers, as risk experts, can also provide information on ways to reduce vulnerability and establish thresholds of acceptable risk for provision of insurance (Courbage and Stahel 2012). This is common practice in the insurance industry today and provides a signal that the CI owner need to reduces its risk in order to obtain insurance coverage.

Proposal #6: Design new multi-year insurance contracts

Insurers could consider designing multi-year insurance (MYI) contracts of three to five years to. The insurance policy would be tied to the structure rather than the property owner, and carry an annual premium reflecting risk that would remain stable over the length of the contract. Property owners who cancel their insurance policy early would incur a penalty cost in the same way that those who refinance a mortgage have to pay a cancellation cost to the bank issuing the mortgage. With an MYI

contract, insurers would have an incentive to inspect the property over time to make sure that building codes are enforced, something they would be less likely to do with annual contracts.

To compare the expected benefits of annual versus multi-year contracts, Jaffee, Kunreuther, and Michel-Kerjan (2010) developed a 2-period model where premiums reflect risk in a competitive market setting. They show that a MYI policy reduces the marketing costs for insurers over 1-period policies and also eliminates the search costs to policyholders should their insurer decides to cancel their coverage at the end of period 1. Should the policyholder learn that the cost of a 1-period policy is sufficiently low to justify paying a cancelation cost, it is always optimal for the insurer to sell a MYI policy and for a consumer to purchase it. The insurer will set the cancellation cost at a level that enables it to break even on those policies that the insured decides to let lapse before the maturity date.

Several factors have contributed to the non-marketability of MYI for protecting properties against losses from fire, theft and large-scale natural disasters. Under the current state-regulated arrangements in which many insurance commissioners have limited insurers' ability to charge risk-based premiums in hazard-prone areas, no insurance company would even entertain the possibility of marketing a policy that was longer than one year. Insurers would be concerned about the regulator clamping down on them now or in the future regarding what price they could charge.[4] Uncertainty regarding costs of capital and changes in risk over time may also deter insurers from providing multi-year insurance.

For the private sector to want to market coverage if the above issues are addressed, there needs to be a sufficient demand to cover the fixed and administrative costs of developing and marketing the product. To empirically test the demand for multi-year insurance, a web-based experiment was undertaken with adults in the United States; most were older than 30 so they were likely to have experience purchasing insurance. The individuals participating in the experiment were offered a choice between 1-year and 2-year contracts against losses from hurricane-related damage. A large majority of the responders preferred the 2-year contract over the 1-year contract, even when it was priced at a higher level than the actuarially fair price. Introducing a 2-year insurance policy into the menu of contracts also increased the aggregate demand for disaster insurance (Kunreuther and Michel-Kerjan 2015).

Proposal #7: Support public-private partnerships for catastrophe insurance

In some necessary instances, the government can provide a back-stop against catastrophic losses to incentivize private insurers and even require private insurers to offer coverage. For example, the Terrorism Risk Insurance Act (TRIA) provides protection to insurers against catastrophic losses from future terrorist attacks. It is important that the loss sharing arrangement be quantified so everyone understands who would pay what should a disaster occur. With regard to TRIA, our

---

[4] Regulators would still monitor insurers to make sure that they have sufficient surplus on hand and are charging a sufficiently high premium to reduce the chance of insolvency to an acceptably low level.

research has shown that the federal government (that is, American taxpayers) will not be responsible for any payments until the total insured commercial losses from a terrorist attack exceed $60 billion. In other words, uninsured firms and insurers will cover the entire losses from future terrorist attacks up to this level.[5] When a state or the federal government is involved in disaster insurance, it can also have a critical role to play in linking insurance and resilience investment.

Proposal #8: Address insurance affordability issues

Critical infrastructure systems are often highly interdependent: a disruption at one utility can affect the entire system as was the case in the Northeast blackout of 2003. A small utility might not have sufficient financial resources and as a result might be underinsured, if insured at all. Over 90 percent of small businesses in the area flooded by Superstorm Sandy in 2012 had no flood insurance. (NYC 2013). Many went bankrupt as a result.

In high-risk areas of the country, risk-based insurance might simply not be affordable for these smaller entities, thus requiring some government intervention to assist them financially with their insurance purchase. Any special treatment given to provide more affordable coverage to facilities in those areas should come from general public funding and not through hidden insurance premium subsidies. Funding could be obtained from several different sources such as general taxpayer revenue or state government depending on "Who should pay?"

Proposal #9: Increase financial resilience through means-tested insurance vouchers

One way to maintain risk-based premiums while at the same time addressing issues of affordability is to offer government-funded means-tested vouchers that cover part of the cost of insurance. The amount of the voucher would be determined by a specific set of criteria as outlined in National Research Council (2015) report on the affordability of flood insurance, as an example. Subsidizing insurance in a transparent way might be less costly to the taxpayers if uninsured losses are covered by post-disaster government relief. Transferring some of the risk to private insurers improves the situation benefits both the policyholder and the government.

6.4 Long-Term Financing of Resilience Investments

Infrastructure facilities at risk may be reluctant to invest in cost-effective loss reduction measures when these involve a high upfront cash outlay. Given budgetary constraints and their focus on short time horizons, it is difficult to convince them that the expected discounted benefits of the investment over the expected life of the facility exceeds the immediate upfront cost. Long-term financing solutions, which can come from both the private and public sectors, can help.

---

[5] For more details on TRIA see Kunreuther, Michel-Kerjan et al. (2014); Michel-Kerjan and Kunreuther (2017).

Proposal #10: Incentivize resilience through regulated rate filings

For critical infrastructure where rates are regulated (such as utilities), regulators could allow an increase in rates to pay for system resilience improvements. Utility commissions, for instance, can encourage resiliency improvements by allowing rate increases to businesses and homeowners to fund these improvements. To maximize benefits to customers, these improvements should focus on reducing cascading failures and improving restoration times and/or reducing the likelihood of failure. Transparency will be an important signal here: utilities could specify what portion of the new rates is for resilience improvement investment on the utility bill customers receive. As part of the process, utilities would inform ratepayers of benefits to them associated with the specific resilience projects they are undertaking. Communities or utility commissions could entice utilities to make resiliency improvements by informing them of benefits to the community and reduced risk to their revenue stream (NIBS 2015).

Proposal #11: Incentivize resilience via enhanced bond ratings

Critical infrastructure owners often seek public revenue-based bonds for implementing projects. Incorporating resilience features into a project can make it less risky and therefore more valuable. If rating agencies that rate the bond recognize this element, they might be willing to increase the bond rating, allowing the organization to access cheaper capital, and/or influencing the amount that can be borrowed at a given rate.

Proposal #12: Issue dedicated "resilience bonds" as a new asset class

In recent years, we have witnessed the emergence of green bonds, which are similar to traditional bonds but intended specifically for infrastructure projects such as "wind farms" or solar projects to generate clean energy that reduce greenhouse gas emission.

The term "resilience bond" focuses on resilience investment was recently introduced (Aerts et al. 2014, Michel-Kerjan 2015). An infrastructure owner or a municipality or state would issue a bond specific to a resilience improving project. Bond investors might be willing to accept a lower return if they agree that by investing in that bond they help a community become more resilient. One relevant example is the City of Los Angeles, which is advocating a seismic resilience bond for fortification of water infrastructure (NIBS 2015).

Proposal #13: Encourage insurers to invest in resilience bonds

Insurers might be the most natural candidates to invest in a resiliency bond as they are large institutional investors, managing more than $30 trillion of assets. By investing their assets in resilience bonds, they can reduce risk faced by some communities or infrastructure systems, thus making them more insurable. In our discussion with several insurers and reinsurers, the main roadblock lies in the regulatory treatments of insurers' assets. Today, regulators in the U.S. and internationally favor short-term low risk investments and infrastructure projects are typically long-term investments.

Proposal #14: Offer public sector long-term mitigation grants and loans

Federal and state governments can help critical infrastructure owners either offset some of the cost of resilience measures or finance them over time. FEMA created the Flood Mitigation Assistance (FMA) program in 1994 to reduce flood insurance claims through measures, such as flood proofing commercial structures or demolishing and relocating property that has received significant damage from a severe flood.

In July 2014, Connecticut initiated its *Shore Up CT* program designed to help residential or business property-owners elevate buildings, retrofit properties with additional flood protection, or assist with wind-proofing structures on property that is prone to coastal flooding. This state program, the first in the United States, enables homeowners to obtain a 15-year loan ranging from $10,000 to $300,000 at an annual interest rate of 2¾ percent. (For more information, see http://shoreupct.org/).

More generally, long-term loans to homes and businesses for mitigation would encourage individuals to invest in cost-effective risk-reduction measures. Consider a property owner who could pay $25,000 to elevate his coastal property from 3 feet below Base Flood Elevation (BFE) to 1 foot above BFE to reduce storm surge damage from hurricanes. If flood insurance is risk-based then the annual premium would decrease by $3,480 from $4,000 to $520. A 15-year loan for $25,000 at an annual interest rate of 2¾ percent would result in annual payments of $2,040 so the savings to the homeowner each year would be $1,440 (that is, $3,480 - $2,040).

Proposal #15: Establish and finance a dedicated National Resilience Fund

A dedicated public sector funding source could support investment in resilience measures to be matched by the private sector. The Kingdom of Morocco launched the first National Resilience Fund (NRF) in 2015, in collaboration with the World Bank that encourages public infrastructure and communities to submit a proposal for co-funding by the NRF for structural (e.g., some flood drainage systems) and non-structural investments (e.g., probabilistic risk assessment or training in insurance mechanisms, early warning system). The applicant must demonstrate pre-approved co-financing from other sources (typically between 30% and 50% of the total cost). In the end, critical infrastructure owners pay 20 to 30% of the total cost, which makes them more likely to pursue the project. From the government's perspective, the co-financing reduces the risks associated with the project and enables them to benefit from the project by a multiplier effect since they only finance 30% of the total cost of the project. For every million dollars of taxpayer money it spends, $2 million more are invested. And since another criterion for the NRF to co-finance resilience projects is for those to demonstrate a benefit/cost ratio higher than one, this is public money well spent.

In the United States, as we discussed in section 5.3, there is not yet a single national entity to coordinate the effort nationally and standardize it across departments and federal and state agencies.

Proposal #16: Offer tax incentives at the local, state and federal government levels

Local, state and federal governments can provide tax incentives to owners of critical infrastructure systems that invest in risk reducing and resilience improving measures. They can also make those conditional. For instance, some tax-deductible expenses may be eligible only to CI owners that demonstrate they also have sufficient insurance coverage to sustain a certain type of disaster (e.g., a 1-in-100 return flood event or a more devastating 1–in- 250 flood).

Proposal #17: Adopt and enforce land ordinances and zoning codes that promote resilience

The public sector can adopt new ordinances and provide accelerated permitting and inspection for projects with enhanced resiliency. They can also promote resilience through zoning codes that encourage location outside of hazardous areas or to higher standards for current and future conditions if new critical infrastructure is built in high-risk areas.

Effective building codes, when enforced, can make an enormous difference in reducing losses from disasters. Following Hurricane Andrew in 1992, Florida reevaluated its building code standards, and coastal areas of the state began to enforce high-wind design provisions for residential housing. Data from Charlotte County reveals that homes that met the wind-resistance standards enforced in 1996 had a claim frequency from Hurricane Charley (2004) that was 60 percent *less* than homes that were built prior to that year (IBHS 2007).

Proposal #18: Establish resilience standards and seals of approval

Recognized and standardized methodologies for assessing the value of loss reductions due to resilience investment will help support many of the aforementioned proposals. The Institute for Business and Home Safety (IBHS) is planning to offer a certification for resilient infrastructure similar to the Leadership in Energy and Environmental Design (LEED) certification offered by the US Green Building Council. NIST, the National Institute of Standards and Technologies, is also working on this certification. (See https://disastersafety.org/fortified/ for more information about this program.)

Infrastructure systems that adopt cost-effective mitigation measures could receive a seal of approval from a certified inspector indicating that the structure meets or exceeds building code standards. A seal of approval could increase the property value of the facility by informing potential buyers that damage from future disasters is likely to be reduced because the mitigation measure is in place.

Proposal #19: Modify the Stafford Act so public infrastructure are better insured

Under the Stafford Act, state and local governments can request funding from the federal government to restore damage to infrastructure and publicly owned buildings. There was a three-month delay after Sandy before Congress agreed to provide $50 billion for this purpose. Given its current posture, it is unclear how much funding Congress would authorize and how long it would

take for them to respond to requests by the affected states and communities after a future disaster. Furthermore, the availability of substantial restoration funds from the public sector following disasters reduces the incentive for infrastructure systems to protect their assets through insurance and other resiliency measures.

The Stafford Act has historically been somewhat restrictive in that it authorizes funding to restore facilities to their pre-disaster condition. Communities that want to modernize roads, bridges and other damaged infrastructure must do so with additional funding from other agencies unless special legislation is approved to allow them to make their community more resilient to future natural disasters with money from the federal government as was the case after Superstorm Sandy when the Federal Transit Administration provided funding, as discussed in Section 5.

Sandy offers an opportunity to rethink the role that the public and private sectors can play for dealing with losses to public sector facilities from natural disasters. Rather than relying primarily on the federal government for assistance, the Stafford Act could be modified to encourage states and local governments to purchase insurance with premiums reflecting the relevant risks.

Proposal #20: Examine private insurance capacity (and willingness) to insure public infrastructure on a larger-scale

Communities that participate in an insurance program are guaranteed to receive pre-specified payments for rebuilding their damaged facilities rather than waiting for Congress to authorize funding that is often inadequate. Communities would then have a financial incentive to make their public buildings and infrastructure more disaster resistant as their insurance premiums would be reduced to reflect the lower expected damage. The public or private sector could provide long-term mitigation loans to spread the upfront costs of these investments over time. If the loss-reduction measures are cost-effective then the annual premium reductions will be greater than the annual cost of the loan. Given the current appetite of the insurance industry to expand its scope – largely driven by the significant amount of excess capital available in the market today, the low-interest rate environments which limit the return on investment of their own portfolio, and the emergence of new technologies that considerable improve risk assessment – and the policy direction set by the new administration, this proposal could be implemented on a large scale in the near future.

SECTION 7. FUTURE WORK

This research project focuses on identifying the barriers that are hindering more effective public-private partnerships, with a focus on the insurance sector, in generating incentives for advancing regional lifeline infrastructure resilience. Through a review of recent literature as well as through conversations with insurers and insurance brokers in the rail and energy sectors, we identified the primary barriers and developed recommendations for mechanisms to promote enhanced resilience. The primary barriers include disincentives associated with government disaster relief, challenges associated with disaster experience, security concerns, politics, and funding. We provided a set of twenty proposals to improve infrastructure resilience through insurance and other incentives.

Future work will focus on the role of insurance in transportation infrastructure in the Northeast, with an in-depth look at the New York Metropolitan Transit Authority (MTA) and the Massachusetts Port Authority (Massport). Transportation infrastructure provides a vital role in community resiliency after a disruption due to the need to move people and supplies efficiently to assist recovery efforts. Transportation infrastructure encompasses transit systems including local and regional rail and bus systems, as well as airports, ports/shipping, and the networks of roadways, bridges, and pedestrian paths. Our work will include an in-depth literature review, survey of infrastructure managers, and follow-up survey of corporate executives to identify barriers and opportunities to improving infrastructure resilience and insurance in the transportation sector and thus foster the homeland security enterprise.

Below is a set of questions we developed for use in interviews of senior executives in relevant global corporations to identify barriers to creating a robust insurance market for lifeline infrastructure sectors. The survey questions address insurers as underwriters as well as insurers as asset managers in two regards:

a) to better understand the obstacles faced by critical infrastructure owners/operators in preparing for and recovering from natural and man-made disasters and ways that they can strengthen their resilience capability. (Obstacles can be economic, behavioral, technical, political or governance related.)

b) to better evaluate how disaster insurance and other financial tools can play a creative role in encouraging preventive actions and providing adequate protection and enhance recovery efforts following a major disruption.

Measures to Reduce Future Losses

1. What actions have you taken to reduce potential losses and facilitate your recovery from natural and man-made disasters or other severe disruptions?

2. What actions are you planning to take in the future to reduce potential losses and facilitate your recovery from natural and man-made disasters or other severe disruptions?

3. What is your current financial protection and recovery strategy to deal with natural and man-made disasters or other severe disruptions? Has it been discussed with the CEO and Board of directors? When?

4. Have you estimated your probable maximum loss resulting from these events? If yes, how much is it? If yes, have you estimated the likelihood of such an event occurring in a given year?

Insurance and Risk Transfer Decisions

1. Do you purchase insurance to cover losses from natural and man-made disasters? If "yes," what is the deductible and coverage limit?

2. Do you buy insurance from a single company or from multiple insurers in a dedicated insurance program placed for you by an insurance broker?

3. Do you feel comfortable that your current insurance strategy is adequate to handle such a loss? If "no," what you would like to change? What are the impediments of doing so?

4. Are you aware of the $200 million catastrophe bond issued by the New York's MTA issued after Superstorm Sandy? Have you considered issuing such a cat bond?

5. Has your insurance program changed as a result of Superstorm Sandy that hit the NY/NJ area in October 2012? If so, in what ways (e.g., lower or higher deductibles or coverage limit, higher costs per dollar of coverage, lack of availability of coverage?)
6. Has your insurance program changed as a result of the Boston Marathon terrorist attacks in April 2013? (e.g., lower or higher deductibles or coverage limit, higher costs per dollar of coverage, lack of availability of coverage
7. Are you self-insured for all types of losses related to natural and man-made disasters? If "yes," do you have a captive?   If self-insurance is partial, how much self-insurance do you have?
8. Do you feel comfortable that your current self-insurance strategy is adequate to handle such a loss? If "no," what you would like to change? What are the impediments of doing so?
9. In a worst-case scenario, how much do you estimate a natural and man-made disasters would cost your company after taking into account your insurance and self-insurance provisions?
10. Do you feel comfortable that your current financial strategy is adequate to handle such a loss?

Post-Disaster Recovery

1. Have you ever received any government post-disaster funding? If Yes, after what disaster?
2. How much public funding did you receive and for what purposes? How long did it take your organization to receive these funds?
3. How much of the post-disaster costs did you were covered by insurance? How long did it take your organization to get these insurance payments?
4. How much did you have to cover from your own surplus?
5. Do you expect to receive any government post-disaster funding should you experience a severe disaster in the next 5 years?

REFERENCES

Aerts, J. C., Botzen, W. W., Emanuel, K., Lin, N., de Moel, H., & Michel-Kerjan, E. O. (2014). Evaluating flood resilience strategies for coastal megacities. *Science*, 344(6183), 473-475.

American Society of Civil Engineers (ASCE) (2013). Reportcard for America's Infrastructure.

Arrow, K. (1963). Uncertainty and the welfare economics of medical care. *American Economic Review*, 53, pp. 941–973.

Artemis (2016). Accessed at: http://artemis.bm

Auerswald, P., Branscomb, L. M., La Porte, T. M., Michel-Kerjan, E. (2005). The challenge of protecting critical infrastructure. *Issues in Science and Technology*, *22*(1), 77-83.

Barletta, L. website (2016). Accessed at: https://barletta.house.gov/media-center/press-releases/barletta-seeks-to-control-costs-of-federal-disaster-responses

Bayot, J. (2005). Payouts hinge on the cause of damage. New York Times, August 31.

Brashear, J.P. et al. (2011). A regional Resilience/Security Analysis Process for the Nation's Critical Infrastructure Systems. ASME Innovative Technologies Institute, LLC.

Bruch, M., Munch, V., Alchinger, M., Kuhn, M., Weymann, M., Schmid, G. (2011). Power Blackout Risks. CRO Forum: Emerging Risk Initiative – Position Paper.

Cabantous, L., Hilton, D., Kunreuther, H., Michel-Kerjan, E. (2011). Is imprecise knowledge better than conflicting expertise? Evidence from insurers' decisions in the United States. *Journal of Risk and Uncertainty*, 42 (2011), pp. 211–232.

Camerer, C., Ho, T. (1994). Violations of the betweenness axiom and nonlinearity in probabilities. *Journal of Risk and Uncertainty*, 8 (1994), pp. 167–196.

Camerer, C., Kunreuther, H. (1989). Decision processes for low probability events: policy implications. *Journal of Policy Analysis and Management*, 8 (1989), pp. 565–592.

Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. *Risk Analysis*, *34*(3), 416-434.

Crossett, K.M., Culliton, T.J., Wiley, P.C., Goodspeed, T.R. (2004). Population Trends Along the Coastal United States: 1980–2008. National Oceanic and Atmospheric Administration, Silver Spring, MD.

Courbage, C., Stahel, W.R. (ed.) (2012). Geneva Association. Extreme events and insurance: 2011 annus horribilis. *The Geneva Reports*, 4(1), 19-164.

Cummins, D., Weiss, M. (2009). Convergence of insurance and financial markets: hybrid and securitized risk-transfer solutions. Journal of Risk and Insurance, 76 (2009), pp. 493–545.

Dávila, O. G., Stithou, M., Pescaroli, G., Pietrantoni, L., Koundouri, P., Díaz-Simal, P., Rulleau, B., Touili, N., Hissel, F., & Penning-Rowsell, E. (2014). Promoting resilient economies by exploring insurance potential for facing coastal flooding and erosion: evidence from Italy, Spain, France and United Kingdom. *Coastal Engineering*, *87*, 183-192.

De Janvry, A. (2015). Quantifying through ex post assessments the micro-level impacts of sovereign disaster risk financing and insurance programs. *World Bank Policy Research Working Paper*, (7356).

ELCON (2004). The Economic Impacts of the August 2003 Blackout.

Entergy (2016). Building a Resilient Energy Gulf Coast: Executive Report. Accessed at: http://www.entergy.com/content/our_community/environment/GulfCoastAdaptation/Building_a_Resilient_Gulf_Coast.pdf.

Four Years After Sandy. (2016). Accessed at: http://www.nj.gov/governor/news/news/552016/approved/20161028a.html

Fischhoff, B., Gonzalez, R.M., Small, D.A., Lerner, J.S. (2003). Judged terror risk and proximity to the World Trade Center. *Journal of Risk and Uncertainty*, 26, pp. 137–151.

Flynn, S.E. (2015). Bolstering Critical Infrastructure Resilience After Superstorm Sandy: Lessons for New York and the Nation. Accessed at: http://www.northeastern.edu/resilience/wp-content/uploads/2015/04/Bolstering-Critical-Infrastructure-Resilience-After-Superstorm-Sandy.pdf .

Francis, T. (2005). CEO Says Allstate adjusts storm plan: interview of Edward Liddy. Wall Street Journal (2005), pp. C1–C3 September 5, 2005.

FTA (2016). FTA Funding Allocations for Hurricane Sandy Recovery and Resiliency. Accessed at: https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/fta-funding-allocations-hurricane-sandy-recovery-and.

Greenwald, B.C., Stiglitz, J.E. (1990). Asymmetric information and the new theory of the firm: financial constraints and risk behavior. *American Economic Review*, 80 (1990), pp. 160–165.

Grossi, P., and Kunreuther, H., eds. (2005). Catastrophe Modeling: A New Approach to Managing Risk. New York: Springer.

Harrington, S.E., Niehaus, G. (2001). Government insurance, tax policy, and the affordability and availability of catastrophe insurance. *Journal of Insurance Regulation*, 19 (2001), pp. 591–612.

Hertwig, R., Barron, G., Weber, E.U., Erev, T. (2004). Decisions from experience and the effect of rare events in risky choice. *Psychological Science*, 15 (2004), p. 534.

Hogarth, R., Kunreuther, H. (1995). Decision making under ignorance: arguing with yourself. *Journal of Risk and Uncertainty*, 10 (1995), pp. 15–36.

Huber, O., Wider, R., Huber, O. (1997). Active information search and complete information presentation in naturalistic risky decision tasks. *Acta Psychologica*, 95 (1997), pp. 15–29.

Intergovernmental Panel on Climate Change (IPCC), 2011. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) <http://ipcc-wg2.gov/SREX/report/>.

Institute for Business & Home Safety (IBHS) (2007). *The Benefits of Modern Wind Resistant Building Codes on Hurricane Claim Frequency and Severity—A Summary Report*.

Insurance Journal, (2015), Amtrak Sponsors $275M Cat Bond for Northeast Storm Surge, Wind, Quake. October 2015.

Jaffee, D., Kunreuther, H., and Michel-Kerjan, E. (2010). "Long Term Property Insurance (LTI) for Addressing Catastrophe Risk." *Journal of Insurance Regulation* 29(07): 167-187.

Johnson, E. J., Shu, S. B., Dellaert, B. C. G., Fox, C., Goldstein, D. G., Häubl, G., Larrick, R. P., Payne, J.W., Peters, E., Schkade, D., Wansink, B., and Weber, E.U. (2012). "Beyond nudges: Tools of a choice architecture." *Marketing Letters* 23(2): 487-504.

Kahneman, D., Tversky, A. (1979). Prospect theory: an analysis of decision under risk. *Econometrica*, 47 (1979), pp. 263–291.

King, D., Ginger, J., Williams, S., Cottrell, A., Gurtner, Y., Leitch, C., Henderson, D., Jayasinghe, N., Kim, P., Booth, K., Ewin, C., Innes, K., Jacobs, K., Jago-Bassingthwaighte, M. & Jackson, L. (2013). Planning, building and insuring: Adaptation of built environment to climate change induced increased intensity of natural hazards, National Climate Change Adaptation Research Facility, Gold Coast, 361 pp.

Kousky, C. (2014). Informing climate adaptation: A review of the economic costs of natural disasters. *Energy Economics*, *46*, 576-592.

Krantz, D., Kunreuther, H. (2007). Goals and plans in decision-making. *Judgment and Decision Making*, 2 (2007), pp. 137–168.

Kunreuther, H. (1989). The role of actuaries and underwriters in insuring ambiguous risks. *Risk Analysis*, 9 (1989), pp. 319–328.

Kunreuther, H., Hogarth, R., Meszaros, J. (1993). Insurer ambiguity and market failure. *Journal of Risk and Uncertainty*, 7 (1993), pp. 71–87.

Kunreuther, H., Michel-Kerjan, E. (2013). Managing the Risk of Catastrophes: Protecting Critical Infrastructure in Urban Areas. Presented to Federal Reserve Bank of New York, November 1, 2013.

Kunreuther, H., Michel-Kerjan (2014). Economics of Natural Catastrophe Risk Insurance. In G. Dionne (ed). Handbook of the Economics of Risk and Uncertainty.

Kunreuther, H., and Michel-Kerjan, E. (2015). Demand for Fixed-Price Multi-Year Contracts: Experimental Evidence from Insurance Decisions. *Journal of Risk and Uncertainty*, 51(2), 171-194.

Kunreuther, H., and Michel-Kerjan, E. (2011). *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes.* MIT Press. Paperback edition.

Kunreuther, H., Miller, L. (1985). Insurance versus disaster relief: an analysis of interactive modeling for disaster policy planning. *Public Administration Review*, 45, pp. 147–154.

Kunreuther, H., Novemsky, N., and Kahneman. D. (2001). "Making Low Probabilities Useful." *Journal of Risk and Uncertainty* **23**(2): 103-120.

Lecomte, E., Gahagan, K. (1998). Hurricane insurance protection in Florida. H. Kunreuther, R., Sr. Roth (Eds.), Paying the Price: The Status and Role of Insurance against Natural Disasters in the United States, Joseph Henry Press, Washington, DC, pp. 97–124.

Lehmann, E. (2012). Risk: State insurance programs continue to grow amid hurricane lull. Accessed on September 27, 2016 at: http://www.eenews.net/stories/1059967092.

Madrian, B. C., and Shea, D. F. (2001). "The Power of Suggestion: Inertia in 401(k) Participation and Savings Behavior." *The Quarterly Journal of Economics* 16(4): 1149-1187.

Marsh (2016) 2016 Terrorism Risk Insurance Report. Accessed at: https://www.marsh.com/content/dam/marsh/Documents/PDF/US-en/2016%20Terrorism%20Risk%20Insurance%20Report.pdf

McGovern, S., Maynard, T., Taylor, G., Smith, N., LeBlanc, A. (2011). Managing the Escalating Risks of Natural Catastrophes in the United States. Lloyd's Report.

Metropolitan Transit Authority (MTA) website (2016). Accessed at http://web.mta.info.

Michel-Kerjan, E. (2010). "Catastrophe Economics: The National Flood Insurance Program." *Journal of Economic Perspectives* 24(4):165-86.

Michel-Kerjan, E. (2015). Effective risk response needs a prepared mindset. Nature, 517(7535), 413.

Michel-Kerjan, E., Kunreuther, H. (2011). Redesigning flood insurance. Science, 333(6041), 408-409.

Michel-Kerjan, E., Kunreuther, H. (2017). A Successful (Yet Somewhat Untested) Case of Disaster Financing: Terrorism Insurance under TRIA 2002-2020. Joint Wharton Risk Center-RFF working paper.

Michel-Kerjan, E., Zelenko, I., Cárdenas, V., Turgel, D. (2011). Catastrophe Financing for Governments: Learning from the 2009–2012 MultiCat Program in Mexico. OECD Working Papers on Finance, Insurance and Private Pensions, No. 9.

Michel-Kerjan, E., Volkman Wise, J. (2011). The Risk of Ever-Growing Disaster Relief Expectations. Paper presented at the annual NBER Insurance Group conference, Cambridge, MA, September 2011. Accessed at: http://nber.org/confer/2011/INSf11/Michel-Kerjan_Volkman_Wise.pdf.

Mills, E. (2005). Insurance in a climate of change. *Science*, *309*(5737), 1040-1044.

Mills, E., Lecomte, E. (2006). From Risk to Opportunity: How Insurers Can Proactively and Profitably Manage Climate Change. Ceres Report, August.

Munich Re (2013). Topics geo, Natural catastrophes 2012, Report, Munich Re, Munich.

Moss, D. (2010). The peculiar politics of American disaster policy: how television has changed federal relief. E. Michel-Kerjan, P. Slovic (Eds.), The Irrational Economist, Public Affairs Books, New York, pp. 151–160 (Chapter 18).

National Institute of Building Sciences (NIBS). (2015). White Paper for Developing Pre-Disaster Resilience Based on Public and Private Incentivization.

National Institute of Building Sciences (NIBS). (2016). An Addendum to the White Paper for Developing Pre-Disaster Resilience Based on Public and Private Incentivization.

National Institute of Technology and Standards (NIST) (2016). Community Resilience Planning Guide for Buildings and Infrastructure Systems. NIST Special Publication 1190. May 2016. Accessed on September 28, 2016 at:

https://www.nist.gov/el/resilience/community-resilience-planning-guides

National Research Council (2015). *Affordability of National Flood Insurance Program Premiums; Report-1* Washington, D.C.: The National Academies Press.

NYC (2013). PlaNYC: A stronger more resilient NYC. New York City, Mayor's Office of Long Term Planning and Sustainability. http://www.nyc.gov/html/sirr/html/report/report.shtml

New York City Panel on Climate Change (2015). "Building the Knowledge Base for Climate Resiliency." *Annals of the New York Academy of Sciences* 1336(1):1–150.

NYC Sandy Funding Tracker. (2016). Accessed at: http://www1.nyc.gov/sandytracker

OECD (2010) OECD. Recommendation: Good practices for mitigating and financing catastrophic risks. Organization for Economic Cooperation and Development, Paris.

OECD (2016). High Level Risk Forum: Evaluation Framework on The Governance of Resilient Critical Infrastructure. Organization for Economic Cooperation and Development, Paris.

O'Hare, P., White, I., & Connelly, A. (2015). Insurance as maladaptation: Resilience and the 'business as usual' paradox. *Environment and Planning C: Government and Policy*, 0263774X15602022.

Palm, R. (1995). Earthquake Insurance: A Longitudinal Study of California Homeowners. Westview Press, Boulder.

Pidot, J. R. (2007). Coastal disaster insurance in the era of global warming: The case for relying on the private market. *Georgetown Environmental Law & Policy Institute*.

Pielke Jr, R., Gratz, J., Landsea, C., Collins, D., Saunders, M., Musulin, R. (2008). Normalized hurricane damage in the United States: 1900–2005. *Natural Hazards Review*, 9, pp. 29–42.

PwC (2016). Rebuilding for Resilience – fortifying infrastructure to withstand disaster.

Repetto R., and Easton, R. (2012). "Climate Change and Damage From Extreme Weather Events," *Environment* 52: 2, 22–33.

Samuelson, W., Zeckhauser, R. (1988). Status quo bias in decision making. *Journal of Risk and Uncertainty*, 1 (1988), pp. 7–59.

Rottenstreich, Y., Hsee, C.K. (2001). Money, kisses, and electric shocks: on the affective psychology of risk. *Psychological Science*, 12 (2001), pp. 185–190.

Slovic, P., Fischhoff, B., and Lichtenstein, S. (1978). "Accident probabilities and seat belt usage: A psychological perspective." *Accident Analysis & Prevention 10*(4): 281-285.

Slovic, P., Monahan, J., and MacGregor, D. G. (2000). "Violence risk assessment and risk communication: the effects of using actual cases, providing instruction, and employing probability versus frequency formats." *Law and Human Behavior 24*(3), 271.

Stone, J. (1973). A theory of capacity and the insurance of catastrophic risks: Part I and Part II. *Journal of Risk and Insurance*, 40, pp. 339–355.

Sunstein, C. (2003). Terrorism and probability neglect. *Journal of Risk and Uncertainty*, 26 (2003), pp. 121–136.

Swiss Re (2011). Sigma No 1/2011: Natural Catastrophes and Man-Made Disasters in 2010.

Thaler, R. H., and Benartzi, S. (2004). "Save more tomorrow™: Using behavioral economics to increase employee saving." *Journal of Political Economy 112*(S1), S164-S187.

Thaler, R., and Sunstein, C. (2008). *Nudge: The gentle power of choice architecture*. New Haven, CT: Yale University Press.

Thaler, R. (1985). Mental accounting and consumer choice. *Marketing Science*, 4 (1985), pp. 199–214.

Tobin, R., Calfee, C. (2005). The National Flood Insurance Program's Mandatory Purchase Requirement: Policies, Processes, and Stakeholders. American Institutes for Research, Washington, DC.

Tversky, A., Kahneman, D. (1973). Availability: a heuristic for judging frequency and probability. *Cognitive Psychology*, 5 (1973), pp. 207–232.

Tversky, A., Kahneman, D. (1991). Loss aversion in riskless choice: a reference-dependent model. *Quarterly Journal of Economics*, pp. 1039–1061.

United Nations (2008). World population prospects: the 2008 revision. United Nations Department of Economic and Social Affairs.

Urlainis, A., Shohet, I. M., Levy, R., Ornai, D., & Vilnay, O. (2014). Damage in critical infrastructures due to natural and man-made extreme Events–A critical review. *Procedia Engineering*, *85*, 529-535.

U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability. (2010). Hardening and Resiliency, US Energy Industry Response to Recent Hurricane Seasons.

U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability. Insurance as a Risk Management Instrument for Energy Infrastructure Security and Resilience. (2013). Accessed on September 12, 2016 at: http://energy.gov/sites/prod/files/2013/03/f0/03282013_Final_Insurance_EnergyInfrastructure.pdf

U.S. Department of Homeland Security (DHS). (2011). FEMA's Process for Tracking Public Assistance Insurance Requirements. DHS Office of Inspector General, OIG-12-18, December 2011.

U.S. Government Accountability Office (2002). Terrorism Insurance: Rising uninsured exposure to attacks heightens potential economic vulnerabilities. Testimony of Richard J. Hillman Before the Subcommittee on Oversight and Investigations, Committee on Financial Services, House of Representatives, February 27, 2002.

U.S. House of Representatives Committee on Transportation and Infrastructure. (2015). Memorandum on Committee Hearing on Rebuilding after the Storm: Lessening Impacts and Speeding Recovery.

Von Peter, G., Von Dahlen, S., & Saxena, S. C. (2012). Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes.

Warner, K., Yuzva, K., Zissener, M., Gille, S., Voss, J., Wanczeck, S. (2013). Innovative Insurance Solutions for Climate Change: How to integrate climate risk insurance into a comprehensive climate risk management approach. Report No. 12. Bonn: United Nations University Institute for Environment and Human Security (UNU-EHS).

Weinstein, N. D., Kolb, K., and Goldstein, B. D. (1996). "Using time intervals between expected events to communicate risk magnitudes." *Risk Analysis* 16, no. 3: 305-308.

Wharton Risk Management Center (2005). *TRIA and Beyond*. Philadelphia, PA. University of Pennsylvania.

Wilbanks T, Fernandez S, Backus G, Garcia P, Jonietz K, Kirshen P, Savonis M, Solecki W, Toole L, Allen M. (2012). Climate change and infrastructure, urban systems. and vulnerabilities. Technical Report for the US Department of Energy in Support of the National Climate Assessment.

Winsemius, H.C., Aerts, J.C., van Beek, L.P., Bierkens, M.F., Bouwman, A., Jongman, B., Kwadijk, J.C., Ligtvoet, W., Lucas, P.L., van Vuuren, D.P. and Ward, P.J. (2016). Global drivers of future river flood risk. *Nature Climate Change*, *6*(4), pp.381-385.

World Bank. Insurance of Public Infrastructure Under Concessions. Disaster Risk Financing Technical Note. (2013).   Accessed   on   September   12,   2016   at: http://siteresources.worldbank.org/EXTDISASTER/Resources/8308420- 1361321776050/Colombia_Concessions_Full_10Oct2013.pdf

Wu, G., Gonzalez, R. (1996). Curvature of the probability weighting function. *Management Science*, 42 (1996), pp. 1676–1690

--- END ---