Performance-based design and risk-based pricing consider natural disasters and recovery over time, explicitly accounting for resilience.

Enhancing Resilience through Risk-Based Design and Benefit-Cost Analysis

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Urban economies depend on shared infrastructure for water, power, communications, and transportation. This critical infrastructure can be impaired by design and construction flaws, deterioration over time, obsolescence, accidents, and excess demand, but this article focuses on damage from natural hazards, which may include earthquakes, tsunamis, volcanic eruptions, tropical cyclones, floods, ice storms, and fire. There is evidence that climate change will exacerbate losses due to hydrometeorological phenomena, primarily tropical cyclones, winter storms, and flooding but also wildfire (USGCRP 2018). To enhance infrastructure resilience to such hazards, we present a risk-based approach, called *performance-based design*, and make the case for considering the benefit-cost ratio and pricing risk in strategies and decisions.

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Recent Catalyzing Events

The 2011 Tōhoku Earthquake and Tsunami

Among the most egregious of recent infrastructure-hazard interactions was the 2011 Tōhoku earthquake and tsunami, which killed 16,000 people (National Police Agency of Japan 2019) and destroyed one of the world's largest nuclear power stations, bringing about the loss of 30 percent of electric power production in the world's third largest economy. Only 9 of the country's 54 nuclear units remain operational (Nippon.com 2018).

The total economic impact of the event is difficult to assess. Direct damage estimates are about $360 billion (in 2011 USD) but do not include widespread economic impacts from loss of agricultural production, business interruption, increased costs of fossil fuel power production to replace lost nuclear capacity, ongoing costs of the Fukushima cleanup, and nonmonetary environmental and psychosocial impacts (e.g., Shigemura et al. 2012; Steinhauser et al. 2014). The cleanup costs alone are estimated to be about ¥70 trillion ($626 billion) over the next 40 years (JCER 2017). Combined with the direct damage estimates, this is the first trillion-dollar natural disaster in history.

Moreover, ten years earlier, research had shown that a similar-sized event in 869 AD had caused tsunami inundation at least 4 km inland (Minoura et al. 2001). And a 2007 study estimated the 99 percent likelihood of a tsunamigenic earthquake magnitude of 8+ within 30 years (Satake et al. 2007).

Finally, it is worth noting that the owner of the Fukushima Nuclear Power Station, Tokyo Electric Power Company (TEPCO), had been forced in 2007 to shut its Kashiwazaki-Kariwa Nuclear Power Station (the world's largest) after the Niigata-Chuetsu-Oki earthquake, and has avoided bankruptcy since the 2011 disaster only because of massive subsidies by the Japanese government (McCurry 2012).

US Hurricanes and Wildfires

In 2005 Hurricane Katrina caused at least 1,200 deaths, $125 billion in damage, and the partial abandonment of New Orleans for several years—even though the event was clearly foreseeable and was due to a "cocktail of natural and human factors" (Bourne 2004). These included decades-long land subsidence and loss of protective marshes and barrier islands, and the failure of flood prevention infrastructure during the event.

Hurricane Sandy (2012) affected 24 states, with particularly severe damage in New York City due to storm surge, which flooded streets, tunnels, and subway lines and cut power in and around the city. US damages amounted to $65 billion. Hurricane Harvey in 2017 matched Katrina as the costliest hurricane on record, with $125 billion in damage (NHC 2018), primarily due to flooding in Houston and Southeast Texas. Hurricane Maria, also in 2017, caused over 3,000 deaths and devastated Puerto Rico, where recovery has been extremely slow. The economic damage from Katrina, Sandy, Harvey, and Maria totaled $450 billion (NHC 2018).

> *The trillion-dollar impacts of the 2011 Tōhoku earthquake and tsunami were predictable and could have been substantially mitigated.*

Catastrophic wildfires in the western states have also been devastating, especially in California, which in 2017–2018 sustained 138 deaths and the destruction of over 31,000 structures (CalFire 2019), with economic losses approaching $30 billion (III 2019). Of interest is the strong correlation between extreme wind conditions and electric power line–caused ignitions, which have led to a number of catastrophic wildfires (Miller et al. 2017; Mitchell 2013; Syphard and Keeley 2015).[1] As a direct result of these wildfires, the largest investor-owned utility in the United States, Pacific Gas & Electric (PG&E), filed for bankruptcy (Bloomberg 2019). PG&E's debtholders and people harmed by the wildfires incurred an unrecoverable loss because of a risk that PG&E failed to adequately fund and instead externalized on them.

Using Performance-Based Design for Multihazard Resilience

To reduce, and in some cases prevent, such catastrophic losses—that is, to contribute to social and

[1] Analyses often show that electric-related ignitions account for only a small fraction of wildland fires (e.g., Prestemon et al. 2013), but this is misleading as most wildland fires are small and quickly suppressed. Strong winds are a common cause of overhead electric line arcing (and ignition) with rapid fire spread, resulting in very large wildfires that are difficult to suppress. Thus, electric-related ignitions account for a large fraction of major wildfires and associated losses (see Kousky et al. 2013).

economic resilience—the design of critical infrastructure needs to be responsive to the attendant risks. A risk-based approach called *performance-based design* (PBD) has emerged in the building design sector over the last several decades, first in fire protection design (Hadjisophocleous et al. 1998; Meacham 1998) and latterly in designs for earthquakes (FEMA 2012; Porter 2003) and wind (Larsen et al. 2016).

Performance-Based vs. Prescriptive Design

PBD has the potential to allow designers to tailor a new facility to achieve selected levels of risk. Expressed in meaningful terms for nonengineering stakeholders, risks to be managed include probabilistic repair costs, life-safety impacts, and loss of function—“the three Ds”: dollars, deaths, and downtime.

> *Performance-based design offers the opportunity to balance up-front cost against long-term resilience in explicit calculations.*

But in practice PBD is rarely used that way. Rather, it is most often used as a form of value engineering (VE)—to reduce the cost of construction while achieving the same degree of life safety that a more conventional, prescriptive design would achieve. That is, one could use PBD to create a better-performing building than prescriptive design would require at the same cost. Instead, PBD has often been used to cut corners—to provide the level of safety that prescriptive design aims for, but at lower cost, by reducing features that would be required under prescriptive design. PBD is mostly being used to save developers and owners money on the up-front construction cost, not to save more occupants’ lives, or reduce future earthquake repair costs, or reduce the downtime that future tenants will suffer.

PBD thus offers greater potential to design for resilience. Like prescriptive design, it recognizes that it may not be possible to avoid extreme loads, but unlike prescriptive design it offers the opportunity via explicit calculation to balance up-front cost against long-term resilience. One can decide how to limit damage under extreme loads so that losses are acceptable and recovery is quick.

PBD has so far been applied largely to building design, although its potential application to other infrastructure has been recognized for some time (Chang 2009). We present a case study of performance-based design of a water supply system subject to earthquake excitation.

Use of PBD for a Water Supply System

We focus on how much of a water supply system to harden against earthquake damage. PBD in general and the Federal Emergency Management Agency guideline P-58 (FEMA 2012) in particular lack built-in norms so that, working on behalf of all or any facility stakeholders, the designer is free to make trade-offs between costs and future performance that seem appropriate.

In the application described here, we design a resilient grid of buried water supply pipes to satisfy standard objectives of benefit-cost analysis for a case with neither fixed input nor fixed output.

- Benefits are measured in terms of the reduction in the present value of future monetary and life-safety losses.
- Costs are measured in terms of the monetary cost to add earthquake-resistant pipe to the system to enhance its capacity to supply water after earthquakes.
- Life safety is valued monetarily using the US Department of Transportation’s value of a statistical life (VSL), essentially the department’s acceptable cost to avoid deaths and nonfatal injuries to unknown people at an unknown future time (sometimes called statistical deaths and injuries) (USDOT 2015).

In a situation without fixed costs or benefits, the optimal design is the largest investment that produces an incremental benefit that exceeds the incremental cost (see, for example, Newnan et al. 2004 for the basics of such a benefit-cost analysis).

Designing a Resilient Water Supply Grid

A study by the National Institute of Building Sciences examined the benefit-cost ratio (BCR) of meeting or exceeding current building codes. It found that model building codes save society $11 per additional $1 spent relative to code requirements of 30 years ago (MMC 2018, referred to as Mitigation Saves 2, or MSv2). It also found that design to exceed current code requirements could save society $4 per additional $1 spent, with local variation in some places exceeding $16 saved

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Exceed common code requirements	Meet common code requirements	Utilities and transportation	Federally funded
Overall Hazard Benefit-Cost Ratio	4:1	11:1	4:1	6:1
Riverine Flood	5:1	6:1	8:1	7:1
Hurricane Surge	7:1	Not applicable	Not applicable	Too few grants
Wind	5:1	10:1	7:1	5:1
Earthquake	4:1	12:1	3:1	3:1
Wildland-Urban Interface Fire	4:1	Not applicable	Not applicable	3:1

FIGURE 1 Benefit-cost ratio (BCR) by hazard and mitigation measure. Source: MMC (2018).

per $1 spent. Figure 1 shows BCR values by peril and mitigation category.

An important goal of this study was to account as comprehensively as possible for benefits and costs, including reductions in property loss, deaths and nonfatal injuries, incidence of posttraumatic stress disorder (PTSD), direct and indirect losses from business interruption (BI), costs for urban search and rescue, insurance costs, and losses associated with environmental and historic impacts. Benefits are recognized for a reasonable lifespan of the mitigation measure (75–100 years, depending on the infrastructure), with three discount rates to account for the time value of money (real cost of borrowing, 3 percent, and 7 percent per year). Death and injury benefits were not discounted. Costs included up-front and long-term maintenance. However, some important nonmonetary benefits were not quantified, such as disconnection of victims from friends, schools, work, and familiar places; loss of family photos and heirlooms; harm to a place's culture and way of life; and other long-term consequences to health and well-being.

Comparison of "As-Is" and Resilient Water Supply Grid

While codes exist for building design, and that design can be enhanced by considering benefit-cost ratios, fewer codes exist for infrastructure, even though benefit-cost considerations can enhance their design. To assess the benefits of enhanced design, the MSv2 study examined BCRs for the following categories of infrastructure: water, wastewater, electricity, telecommunications, roads, and railroads. Four perils were considered: earthquake, flooding, wind, and fire at the wildland-urban interface (WUI). We discuss the study of the benefits and costs of implementing a resilient grid in an urban water supply network subjected to earthquake. That is, we consider whether it is cost effective to improve network resilience by reducing seismic vulnerability or otherwise improving all or some distribution trunk lines, thereby forming a resilient grid (Davis 2017).

A three-phase approach was used in the study:

1. Phase 1: The study examined an idealized water supply network, sized to be generally representative of a medium-sized US city, in order to draw general conclusions for cities in high seismic hazard locations. Figure 2 shows the schematic network, termed the *as-is network*, which was examined for earthquake resilience. The figure shows that a transmission line brings raw water from the source (a reservoir) to a treatment plant. Treated water is conveyed to terminal reservoirs and then the distribution network, where trunk lines convey water to distribution lines. (Some or all of the trunk lines can form the resilient grid.) The model region is square-symmetric to eliminate bottlenecks or other complicating factors. The size and spacing of distribution pipes and trunk lines accommodate typical average day demands including ordinary fire flows (figure 3).

2. Phase 2: The as-is network was stressed with random breaks and leaks resulting from earthquake excitation together with extraordinary fire demands (the phenomenon of fire following earthquake; TCLEE

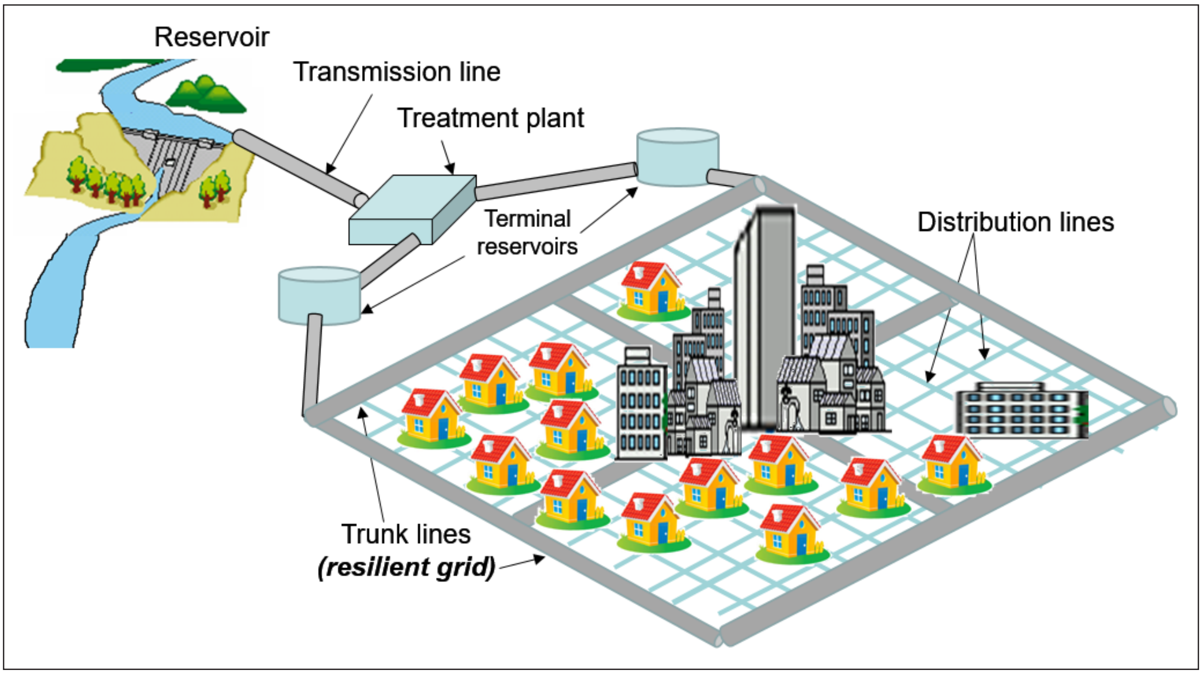

FIGURE 2 Schematic of "as-is" water supply network: transmission line brings raw water from source (reservoir) to treatment plant; treated water is conveyed via trunk lines to terminal reservoirs and then to distribution network. Some or all trunk lines can form the resilient grid.

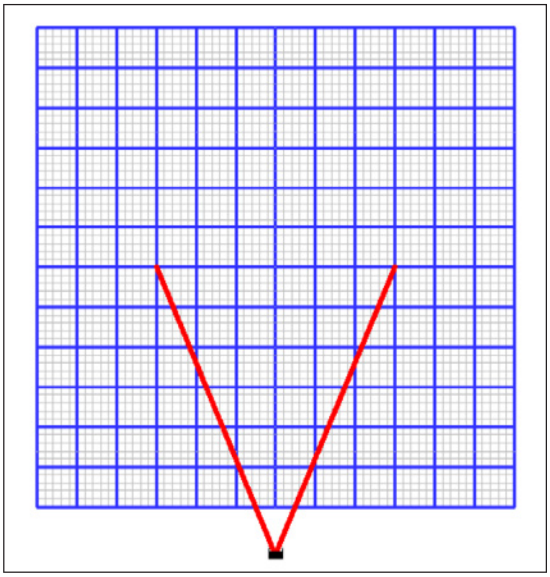

FIGURE 3 Study grid intended to be representative of the water distribution system of a medium-sized city. It is 36,000 ft (6.82 miles) on a side, with 61 lines of N-S and E-W distribution pipes regularly spaced 600 ft apart (grey lines). Trunk lines (the resilient grid), shown in bold blue, are placed every 5 distribution pipes, in a grid of 3,000 ft. The source (small black box), south of the grid, supplies two terminal reservoirs (at the upper ends of the red lines) placed symmetrically in the East and West parts of the city via transmission lines (red; the transmission lines are not part of the model). The distribution and trunk grids are connected only at intersections.

2005). Under earthquake excitation[2] the as-is water system, which was not designed with earthquake in mind, incurs repair costs as well as insufficient water pressure to both continue serving all its customers and provide firefighting water supply (figure 4), causing loss of service and leading to larger fires after an earthquake and longer time to recovery.

3. Phase 3: The as-is system was improved to form a resilient grid. The improvement consists of replacing selected trunk lines with lower-vulnerability pipe that experiences less damage when subjected to earthquake excitation. For example, cast iron or asbestos cement trunk lines might be replaced with earthquake-resistant ductile iron pipe (ERDIP). The shortfall (if any) and resulting consequences of this resilient grid system, stressed with the same scenario, were compared with those of the as-is system to determine benefits of the improvement.

The difference in loss of service, fire size, time to recovery, and costs between the as-is and resilient grids is a measure of the benefits of the resilient grid. These benefits include reduced losses in (a) water system

[2] Denoted using the Modified Mercalli intensity (MMI) scale, although calculations were performed using more detailed engineering parameters (see Porter 2018).

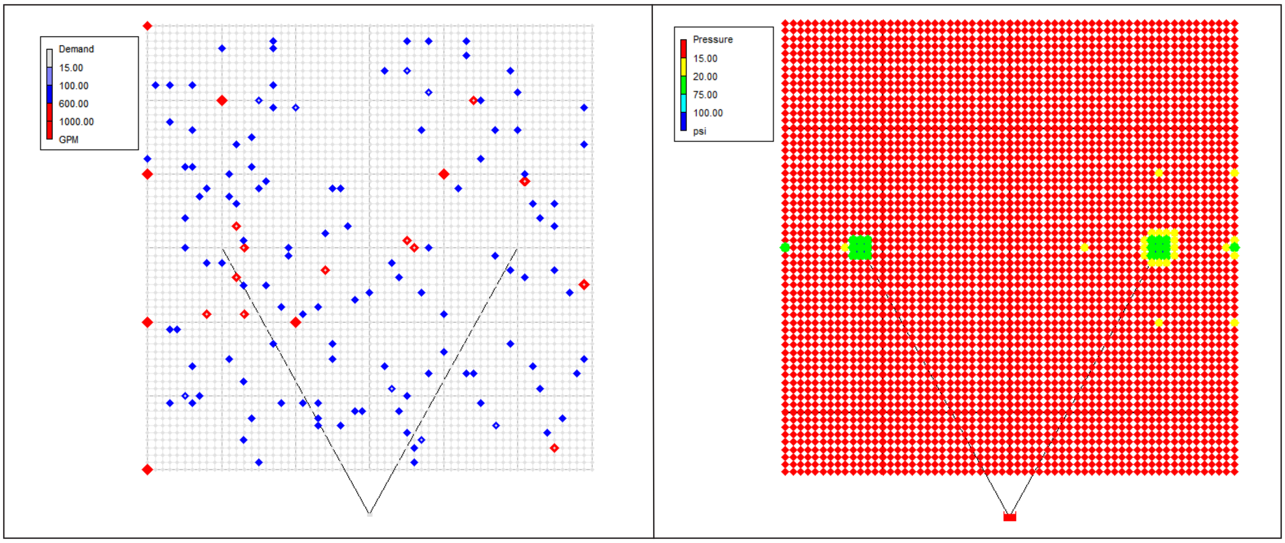

FIGURE 4 Under an MMI 8 earthquake the as-is design (left) sustains 111 distribution and 9 trunk line repairs (blue diamonds) and 21 ignitions (red diamonds, not all shown at this scale), changing the pressure distribution (right): red indicates nodes with inadequate pressure for firefighting, yellow barely adequate, and green adequate. Reprinted with permission from MMC (2018).

repair costs, (b) fire-related property losses, (c) direct BI associated with lack of water service and fire damage, (d) indirect BI losses for the rest of the economy that does business with customers who lose water service or suffer fire damage, and (e) deaths, injuries, and instances of PTSD resulting from fire after the earthquake. These benefits were then converted to equivalent dollar amounts per year by integrating benefits with hazard frequency.

Calculating the Financial Benefits of Resilience

The study team estimated the present value of benefits over a time horizon by applying a discount rate equal to the real cost of borrowing. The present value of benefits divided by cost was the BCR for the resilient grid, as shown in table 1, which presents BCRs for scenario events, and for four West Coast cities (table 2) considering their actual seismic hazard. As one would expect, table 2 shows that resilient infrastructure is more cost beneficial the greater the seismic hazard: San Francisco and Los Angeles, which have very high seismic hazard, benefit much more than, say, Portland (OR), where seismicity is more moderate ("moderate" as averaged over many years; it should be noted that Portland's and Seattle's seismic hazard is currently much greater than "moderate" because of an anticipated very large Cascadia Subduction Zone earthquake; see Atwater et al. 2015).

Study observations included the following:

- The major benefit of the resilient grid was due to improved supply of firefighting water.
- The benefit of the resilient grid was due to the lack of fire service capacity. If the fire service increased its capacity—for example, by moving water via tanker trucks or portable water supply systems—the resilient grid was less beneficial.
- The observation above reinforced the point that the resilient grid concept cannot be solely a water department initiative but needs to be pursued in close cooperation with the fire service.
- The resilient grid was quite likely to significantly reduce restoration time of the water supply to customers.
- Closer spacing of the resilient grid (e.g., trunk lines at every fifth or sixth distribution line rather than every tenth) may not significantly increase the BCR: although it increased benefits, it also increased costs.
- The findings on BCRs were based on the overly conservative assumption that the resilient grid required the replacement of 100 percent of the trunk lines. If only a portion of the resilient grid required replacement (e.g., 50 percent of the existing trunk lines were considered of low vulnerability and therefore did not require replacement), the BCRs would have been doubled.

As the study notes, the BCRs are based on long-term seismic hazard probabilities, not time-dependent prob-

TABLE 1 Summary of losses and benefits with and without resilient grid for a given earthquake ($ millions)

	Modified Mercalli intensity (MMI)				
	VI	VII	VIII	IX	X
Losses without resilient grid	none	$138	$19,007	$53,224	$152,774
Losses with resilient grid	none	$119	$8,667	$33,517	$132,993
Benefit of resilient grid	none	$19	$10,341	$19,707	$19,782
Cost of resilient grid	$403	$403	$403	$403	$403
Benefit-cost ratio	0	0.05	25.7	48.9	49.1

TABLE 2 Summary of benefit-cost ratios for several interest rates, four West Coast cities

Real discount rate (per annum)	San Francisco	Los Angeles	Portland OR	Seattle
2.17%	8.3	6.3	0.59	1.73
3.00%	6.4	4.9	0.46	1.34
7.00%	2.9	2.2	0.2	0.6

abilities. All four cities are judged to be at high risk of a major earthquake in the next several decades, which if considered would increase the BCRs significantly.

The Value of Pricing Risk

More resilient infrastructure design can clearly be achieved through the PBD approach, which is in the early stages of being implemented in a few infrastructure systems (Davis 2017).

For much infrastructure, however, the lack of standards vis-à-vis system performance given natural hazards means that resilience is not really considered. For example, electric power system reliability is measured using metrics such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) (IEEE 2012), but these are only empirical measures of past performance and don't consider prospectively the impact of catastrophic natural hazards. As a result, electric utilities and the public may be under an illusion about the reliability of electric power (Larsen et al. 2015; Mauldin 2015).

Costs of Externalized Risk

An extreme example is Fukushima, where TEPCO's pretsunami electricity pricing did not include a charge for the risk of meltdown and associated cleanup. Had such risk been priced into the cost, (a) TEPCO may well have found it cost effective to build better tsunami protection and (b) authorities would have had a reserve to pay for the postdisaster costs.

The same would apply for PG&E's electricity pricing in WUI areas: not only would such pricing apply to locals, but some charge would apply to the broader customer base for bulk transmission that creates risk in crossing the WUI to serve urbanized areas.

An example of risk charging in a changing environment is the increasing transportation of oil by rail in the United States. Accidents involving oil tank car trains can be very serious. The most well-known recent example was the July 2013 derailment in the Québec town of Lac-Mégantic of a freight train operated by the Montreal, Maine and Atlantic Railway (MMA). The accident killed 47 people and caused widespread destruction estimated in excess of $100 million.

The combination of increasing shipments by rail and the higher accident rate by rail (Mason 2018) has raised significant concerns about transportation safety and potential impacts to the environment (Frittelli et al. 2014; Hughlett 2019; IRSWG 2014; Millar 2018), although recommended fixes are so far limited to more frequent inspections and improved emergency response (IRSWG 2014). That is, the recommended fixes aim to make a disaster less likely to occur in the first place and to decrease the loss if it does occur, but they do not address the question of who bears the risk in these situations. While the oil and rail companies profit, and the general public benefits from the cost-effective distribution of energy, a disproportionate amount of the risk (virtually all) is borne by persons and property in direct proximity to the rail line (Gelfand 2018).

In economic terms, MMA externalized its risk: it imposed the negative outcomes of its cost-cutting practices on parties who did not choose to incur them.

Equitable Risk Pricing

Economists often urge governments to adopt policies that internalize an externality so that costs and benefits mainly affect parties who choose to incur them: when there is no externality, allocative efficiency is achieved. Internalizing risks also seems more equitable to outside parties.

One approach to encourage both risk equity and infrastructure PBD is the creation of a risk tax, analogous to the carbon tax (see www.carbontax.org) adopted by many industrialized countries.[3] Just as a carbon tax encourages carbon-reducing economic development and provides funding for carbon-reducing activities, a risk tax would encourage risk-reducing economic development and provide funding for risk mitigation. While the chances in the near term for a US risk tax are probably lower than for a national carbon tax, some states, communities, and enlightened corporations are implementing carbon-based taxing or policies,[4] so a path does exist. The concept of a risk tax deserves discussion.

Synthesis: A Spatiotemporal Model for Resilient Design

Most approaches to PBD and resilience are still rather parochial: building performance is typically decided only in the context of a particular building, and infrastructure performance only in the context of a single facility or, at best, the operator or agency. One might suppose that such an approach will still tend toward the greater good, based on the hypothesis that the invisible hand of the market (from Adam Smith's *Theory of Moral Sentiments* and *Wealth of Nations*) will produce nearly the same outcomes from economic actors such as MMA and PG&E as the companies might have produced from motives of pure humanity or justice. But the evidence from Lac-Mégantic, the 2018 California wildfires, and countless other examples undermines that hypothesis.

Recognition of the lack of this broader perspective and the failure of the invisible hand adequately to protect society from disasters is leading to demands for better longer-term systemic performance, such as Los Angeles' Resilience by Design program (Mayoral Seismic Safety Task Force 2014; and see Jones and Aho 2019 in this issue). What is required, whether for the urban fabric of buildings or for the system of urban infrastructure systems, is a recognition of the difference between the sum of failures of many buildings and infrastructure facilities in a community when treated as individually independent, and the totality of the impact of their simultaneous loss (considering correlations and negative synergies), as can and does occur in earthquakes, hurricanes, floods, and wildfires. The 2011 earthquake in Christchurch, New Zealand, Hurricane Maria (2017) in Puerto Rico, and the Paradise (CA) conflagration (2018) all bear witness to the compound effects of mass destruction. From a utilitarian perspective, PBD must count costs and benefits to all affected parties, not only developers, owners, or other authorities.

A risk tax would encourage risk-reducing economic development and provide funding for risk mitigation.

A PBD framework that considers the correlated effects of natural hazards, structural performance, and economics of all buildings in an urban region is needed. Theoretical models show that even small changes in the urban form, when regions of high hazard are considered, can greatly reduce urban lifecycle costs (Scawthorn et al. 1982). Even this approach has its limitations in that it is only a snapshot in time, and a more holistic PBD would consider natural disasters and recovery over time, explicitly accounting for resilience.

References

Atwater BF, Musumi-Rokkaku S, Satake K, Tsuji Y, Ueda K, Yamaguchi DK. 2015. The orphan tsunami of 1700: Japanese clues to a parent earthquake in North America, 2nd ed. USGS Professional Paper 1707. Seattle: University of Washington Press.

[3] The current list is posted at https://en.wikipedia.org/wiki/Carbon_tax.

[4] These states and companies are listed at https://en.wikipedia.org/wiki/Carbon_tax#United_States.

Bloomberg. 2019. PG&E officially files for bankruptcy under the financial strain of California wildfires. Fortune, Jan 29.

Bourne JK Jr. 2004. Gone with the water. National Geographic, October.

CalFire. 2019. Top 20 most destructive California wildfires. Sacramento: California Department of Forestry and Fire Protection. Online at www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Destruction.pdf.

Chang SE. 2009. Infrastructure resilience to disasters. The Bridge 39(4):36–41.

Davis CA. 2017. Developing a seismic resilient pipe network using performance-based seismic design procedures. Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference, Oct 18–19, Tainan, Taiwan. Taipei: National Center for Research on Earthquake Engineering.

FEMA [Federal Emergency Management Agency]. 2012. Seismic Performance Assessment of Buildings, vol 1: Methodology (P-58-1). Washington.

Frittelli J, Andrews A, Parfomak PW, Pirog R, Ramseur JL, Ratner M. 2014. US rail transportation of crude oil: Background and issues for Congress. Washington: Congressional Research Service.

Gelfand A. 2018. Bomb trains: The dangers of rail transport of crude oil. Hopkins Bloomberg Public Health, fall.

Hadjisophocleous GV, Benichou N, Tamim AS. 1998. Literature review of performance-based fire codes and design environment. Journal of Fire Protection Engineering 9:12–40.

Hughlett M. 2019. Safety officials concerned by sharp increase in oil train traffic from Canada. Star Tribune (Minneapolis), Feb 9.

IEEE [Institute of Electrical and Electronics Engineers]. 2012. IEEE guide for electric power distribution reliability indices (Standard 1366-2012). Piscataway NJ.

III [Insurance Information Institute]. 2019. Facts + Statistics: Wildfires. New York. Online at https://www.iii.org/fact-statistic/facts-statistics-wildfires.

IRSWG [Interagency Rail Safety Working Group]. 2014. Oil by rail safety in California: Preliminary findings and recommendations. Sacramento.

JCER [Japan Center for Economic Research]. 2017. The Fourth Industrial Revolution in Japan: Does Japanese research and development contribute to economic growth? Policy proposal, Mar 13. Tokyo.

Jones LM, Aho M. 2019. Resilience by Design. The Bridge 49(2):52–59.

Kousky C, Greig K, Lingle B, Kunreuther H. 2018. Wildfire costs in California: The role of electric utilities. Issue Brief. Philadelphia: Wharton Risk Management and Decision Processes Center, University of Pennsylvania.

Larsen PH, LaCommare KH, Eto JH, Sweeney JL. 2015. Assessing Changes in the Reliability of the US Electric Power System. Berkeley: Lawrence Berkeley National Laboratory.

Larsen R, Klemencic R, Hooper J, Aswegan K. 2016. Engineering objectives for performance-based wind design. Proceedings of the 2016 Geotechnical and Structural Engineering Congress, Feb 14–17, Phoenix.

Mason CF. 2018. A comparison of the risk of transporting crude oil: Rail vs. pipeline. International Association for Energy Economics Energy Forum, Second Quarter.

Mauldin P. 2015. US power reliability: Are we kidding ourselves? T&D World, Jan 14.

Mayoral Seismic Safety Task Force. 2014. Resilience by Design. Los Angeles: Office of the Mayor.

McCurry J. 2012. Fukushima owner saved from collapse by Japanese government. The Guardian, May 9.

Meacham BJ. 1998. The Evolution of Performance-Based Codes and Fire Safety Design Methods. NIST-GCR-98-761. Gaithersburg MD: National Institute of Standards and Technology.

Millar F. 2018. Oil train and refinery safety: Don't roll the dice that we'll avoid disasters. Star Tribune (Minneapolis), Jul 6.

Miller C, Plucinski M, Sullivan A, Stephenson A, Huston C, Charman K, Prakash M, Dunstall S. 2017. Electrically caused wildfires in Victoria, Australia are over-represented when fire danger is elevated. Landscape and Urban Planning 167:267–274.

Minoura K, Imamura F, Sugawara D, Kono Y, Iwashita T. 2001. The 869 Jogan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. Journal of Natural Disaster Science 23(2):83–88.

Mitchell JW. 2013. Power line failures and catastrophic wildfires under extreme weather conditions. Engineering Failure Analysis 35:726–735.

MMC [Multihazard Mitigation Council]. 2018. Natural Hazard Mitigation Saves: 2018 Interim Report. Washington: National Institute of Building Sciences.

National Police Agency of Japan. 2019. Police countermeasures and damage situation associated with 2011 Tohoku district. Tokyo.

Newnan DG, Eschenbach TG, Lavelle JP. 2004. Engineering Economic Analysis. New York: Oxford University Press.

NHC [National Hurricane Center]. 2018. Costliest US tropical cyclones tables updated. Miami.

Nippon.com. 2018. Japan's nuclear power plants, Jul 19. Tokyo.

Porter KA. 2003. An overview of PEER's performance-based earthquake engineering methodology. Proceedings of the Ninth International Conference on Applications of Statistics and Probability in Civil Engineering, Jul 6–9, San Francisco.

Porter KA. 2018. A new model of water-network resilience, with application to the HayWired scenario. In: The HayWired Earthquake Scenario—Engineering Implications, eds Detweiler ST, Wein AM. Scientific Investigations Report 2017-5013-I-Q. Reston VA: US Geological Survey.

Prestemon JP, Hawbaker TJ, Bowden M, Carpenter J, Brooks MT, Abt KL, Sutphen R, Scranton S. 2013. Wildfire ignitions: A review of the science and recommendations for empirical modeling. General Technical Report SRS-GTR-171. Asheville NC: USDA-Forest Service, Southern Research Station.

Satake K, Sawai Y, Shishikura M, Okamura Y, Namegaya Y, Yamaki S. 2007. Tsunami source of the unusual AD 869 earthquake off Miyagi, Japan, inferred from tsunami deposits and numerical simulation of inundation. American Geophysical Union Fall Meeting (abstract #T31G-03), San Francisco.

Scawthorn C, Iemura H, Yamada Y. 1982. The influence of natural hazards on urban housing location. Journal of Urban Economics 11:242–251.

Shigemura J, Tanigawa T, Saito I, Nomura S. 2012. Psychological distress in workers at the Fukushima nuclear power plants. JAMA 308(7):667–669.

Steinhauser G, Brandl A, Johnson TE. 2014. Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts. Science of the Total Environment 470:800–817.

Syphard AD, Keeley JE. 2015. Location, timing and extent of wildfire vary by cause of ignition. International Journal of Wildland Fire 24:37–47.

TCLEE [Technical Council on Lifeline Earthquake Engineering]. 2005. Fire following earthquake. Monograph no. 26, eds Scawthorn C, Eidinger JM, Schiff AJ. Reston VA: American Society of Civil Engineers.

USDOT [US Department of Transportation]. 2015. Guidance on treatment of the economic value of a statistical life (VSL) in US Department of Transportation analyses – 2015 adjustment, Jun 17. Washington. Online at https://www.transportation.gov/sites/dot.gov/files/docs/VSL2015_0.pdf.

USGCRP [US Global Change Research Program]. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, vol II, eds Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, Stewart BC. Washington.