A Bridge to Prosperity: Resilient Infrastructure Makes a Resilient Nation*

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Abstract

As we Americans revitalize our aging infrastructure through both renovations and new construction, we must develop a long-term vision. Simultaneously the vision must acknowledge our investment in existing structures, increase America’s resiliency, reap the benefits of improved societal efficiencies, and strengthen America on the world stage. Simply patching potholes, painting bridges, building power plants, adding lanes to interstates, and propping up utility poles are insufficient and unacceptable piecemeal solutions.

To achieve the vision of a resilient America, we must commit to a sustained effort across geographic, political, and economic boundaries, across infrastructure sectors, and across technical discipline. We must develop and implement technologies, processes, standards, codes, and laws that enable the vision. But, before we commit precious resources, we need a blueprint at multiple scales, requiring a national discourse on priorities and technological assessments that provide solid, compelling evidence for a positive cost/benefit ratio.

Traditionally, science and technology have provided a toolbox of new technologies, new materials, new monitoring, better controls, and optimization models. The Department of Homeland Security’s (DHS’s) Science and Technology Directorate (S&T) will continue to provide new toolbox-advances that will shape the discussion of how we achieve a resilient infrastructure. More important, science and technology can contribute to shaping our blueprint by instilling scientific rigor into the process that will shape our future.

S&T’s role in understanding interdependencies at multiple scales, setting standards, examining underlying assumptions, informing decisions with data, envisioning possible future technologies, developing architectures, improving risk assessment, analyzing alternatives, and running scenarios is critical to optimize and rationalize the vision. S&T can also contribute to initiatives to provide 21st century governance, financing, manufacturing, and revitalization business models.

Intelligent and expansion of America’s infrastructure requires innovation on many physical scales, from the nano- to global. This paper addresses the scope and scale of the challenges while providing considerations for developing plans. Scientists and engineers have a voice and an important role in shaping this vision. The science and technology community must participate in the discourse and provide guidance on the technical, economic, and social possibilities for our future.

Note: This article discusses technologies, concepts, and policies of interest to the homeland security community. The views expressed here are those of the author. Reference herein to any specific commercial products, processes, equipment, or services does not constitute or imply its endorsement, recommendation, or favoring...
Our Aging Infrastructure

Infrastructure ages. Priorities change. Disasters, accidents, and catastrophes occur. Nonetheless, in the face of these forces, America must maintain its infrastructure. A balanced replacement/renovation plan and program would maintain our infrastructure at an acceptable target average age while shifting toward projected capacities and demands.

America has deferred needed maintenance for many years, the infrastructure is aging, and we are beginning to suffer the consequences. The American Society of Civil Engineers (ASCE) estimated\(^1\) in 2009 that the US has $2.2 trillion in deferred maintenance, repairs, and needed infrastructure upgrades. Our investment in transportation has not kept pace with demand. Highways are one example, as shown in Figure 1.\(^2\)

Despite compelling data from ASCE, various governmental organizations, and many others, we continue to slip further behind.

While the decline is troubling, we face other challenges in growth:

- Vehicle traffic is growing at 1.4 percent per year.
- 2035 will see 80 percent more freight.
- By 2020, the number of shipping containers handled will double.\(^3\)

Moreover, societal changes will present challenges:

- Electric vehicles will force changes in the way we finance highways. As fewer vehicles use petroleum, how will we replace the gasoline tax?

\(^1\) American Society of Civil Engineers Report Card for America’s Infrastructure, 2009. Note: Content and links from all Web sites are current as of the date they were accessed in May 2009.


\(^3\) Stanley Gee, Acting Commissioner, NY State Department of Transportation, Keynote Address to The New York State Infrastructure Summit, NY, NY, 12 May 2009.
As Americans age, and our activity patterns change, the infrastructure demands will change.

Population is migrating to the coasts; coastal counties constitute only 17 percent of the total land area of the United States (not including Alaska) but account for fully 53 percent of the total population, and that figure is rising.

Information technology will change our habits and locations for work, shopping, recreation, and communications. These changes will affect demand on telecommunications, shipping, and movement of people in ways we cannot reliably predict:

Every year public- and private-sector organizations spend hundreds of billions of dollars to operate and maintain power, drinking water, waste water, transportation, and telecommunications systems. At least $285 billion was invested in these efforts in 2004 alone. Nonetheless, this was inadequate, as evidenced by the deteriorating condition of these systems. The resources available to renew and restructure these systems will be limited for the foreseeable future, and hard investment choices will need to be made.

“We need to fix the way we fix things.” America and many other countries have responded to the economic crises of 2008–2009 with stimulus packages that, among other goals, fund infrastructure. In many cases, the funding is designed to create jobs by funding “shovel ready” projects that have already been planned. These near-term fixes are needed, given the circumstances, but as America revitalizes its aging infrastructure through both renovations and new construction, we must develop a long-term vision. The vision must simultaneously maintain existing structures, increase America’s resiliency, reap the benefits of improved societal efficiencies, and strengthen America on the world stage. The Dwight D. Eisenhower National System of Interstate and Defense Highways, now more than 50 years old, is a premier example of a bold, national vision. Simply patching potholes, painting bridges, building power plants, adding lanes to interstates, and propping up utility poles is insufficient and unacceptable.

President Obama’s administration is committed to resilient infrastructure:

Promote the Resiliency of our Physical and Social Infrastructure

Ensuring the resilience of our critical infrastructure is vital to homeland security. Working with the private sector and government partners at all levels will develop an effective, holistic, critical infrastructure protection and resiliency plan that centers on investments in business, technology, civil society, government, and education. We will invest in our Nation’s most pressing short and long-term infrastructure needs, including modernizing our electrical grid; upgrading our highway, rail, maritime, and aviation infrastructure; enhancing security within our chemical and nuclear sectors; and safeguarding the public transportation sys-

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4 Deborah Epstein Popper and Frank J. Popper, The Great Plains: From Dust to Dust, Planning (December 1987). The “Buffalo Commons” asserted that human population of the U.S. high plains was unsustainable, that people would continue to migrate away toward population centers, and that a large swath of America’s midlands should be returned to a vast nature preserve. The concept was not well-received in the affected region.


8 Rob Puentes (Brookings Institution) at a rollout event for Memo to the President: Invest in Infrastructure for Long-Term Prosperity, Brookings Institution, Washington, DC, 12 January 2009.

9 Aerial picture of the "folded" cloverleaf at Interstate 80 in Pennsylvania from Pennsylvania Department of Transportation. Used with permission.

10 White House Homeland Security and Counterterrorism issues page.
tems that Americans use every day.

Science and technology provide a toolbox of new technologies, new materials, new monitoring, better controls, integration of systems, and optimization models. These advances will shape the discussion on how we achieve a resilient infrastructure.

This paper discusses the need for and benefits of working toward resilient infrastructure by discussing broad concepts and specific examples.

**Homeland Security Benefits of a Resilient Infrastructure**

Resiliency is the foundation of preparedness. A resilient society can withstand and/or recover from natural disasters, terrorist attacks, and infrastructure failures. A resilient society can face the challenges of the upcoming decades. Resiliency goes hand-in-hand with capacity. As we improve our resiliency, we simultaneously improve reserve capacity and can design for future demand. Resiliency is a core component of quality of life, prosperity, competitiveness, and security.

The benefits of resiliency are illustrated in Figure 2,11 where a combination of hardening, redundancy, response time, and rate of recovery combine to define the integrated area or loss. Resiliency can optimize some or all of these components to minimize the loss.

Society’s investment priorities must satisfy broad sectors of the population as potholes are fixed, transportation is improved, life’s amenities become more reliable, and costs are reduced. That is the small view.

The big view envisions a strong America that capitalizes upon our knowledge and service strengths to contribute to the global economy, has robust internal defenses, and continues to be a major force in the world. The vision should be: America will incorporate a resiliency ethic into construction, infrastructure, business models, and government policies. The objective is to increase America’s resiliency and reap the benefits of improved societal efficiencies and a strengthened America on the world stage.

**Costs of Resiliency.** Infrastructure costs money. Resilient infrastructure may have a higher capital cost because it requires added safety factors, extra reserve capacity, redundant systems, backup operators, and other costs.

**Costs if we do not rise to this challenge.**12 If America’s infrastructure is not resilient, if we continue to defer maintenance, if we cannot meet the coming societal and business demands, if we cannot efficiently transport people and goods, if we cannot communicate effectively, and if we try to run America on a shoddy infrastructure, we are doomed to a downward spiral in our economy, standard of living, and world stature.

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11 Personal communication, ME Hynes, DHS Science and Technology Directorate (S&T), May 2009; originally conceived 12 September 2001.
12 Pothole image used with permission.
The hidden costs of lost time and productivity, excess pollution, and general ill-will are incalculable. From our own personal experience, we all know the psychic and disruptive toll exacted by slow traffic, delayed deliveries, power outages, and poor phone connectivity. These are inconvenient annoyances. New Orleans suffered mightily through Hurricane Katrina, and in the years after, America needs to ponder the implications of a broken infrastructure, like New Orleans, with sporadic power, unsanitary conditions, constipated transportation, and intermittent food delivery.

**Thinking across vast differences of scale.** Scientists and engineers tend to work in reasonably tight-scale domains. Synthetic chemists think at a molecular scale. Physicists study subatomic particles. Engineers build structures in the 10- and 100-m scale. Transportation planners look for routes that are hundreds of kilometers long. Computer scientists design for nanosecond pulses. Increasingly we all need to be thinking and planning across all these scales. Scientists must visit other scales to consider implications of their work and look for new approaches. Engineers must think more broadly across scales to consider chemical degradation of structural elements and also the systems of systems that have an impact upon, and are impacted by, the discrete structure being considered. Get out of your comfort zone! Table 1-3 provide notional illustrations of scaling across length, time, and people.

**Table 1: Powers of Ten—Length**

<table>
<thead>
<tr>
<th>Exponent (10^x)</th>
<th>Common Unit</th>
<th>Category</th>
<th>Example(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>Å</td>
<td>atoms</td>
<td>bonds</td>
</tr>
<tr>
<td>-9</td>
<td>nm</td>
<td>molecules</td>
<td>octane</td>
</tr>
<tr>
<td>-8</td>
<td></td>
<td></td>
<td>nanoparticles (1-100 nm)</td>
</tr>
<tr>
<td>-7</td>
<td></td>
<td></td>
<td>H1N1 virus diameter (~100 nm); HEPA filtration (~300 nm)</td>
</tr>
<tr>
<td>-6</td>
<td>µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5</td>
<td></td>
<td>materials failure</td>
<td>Crack propagation starts.</td>
</tr>
<tr>
<td>-4</td>
<td></td>
<td>human hair diameter</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>mm</td>
<td></td>
<td>gusset plates on I-35W bridge (&lt;19mm)</td>
</tr>
<tr>
<td>-2</td>
<td>cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>m</td>
<td>components</td>
<td>windows</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>beams</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>km</td>
<td>structures</td>
<td>buildings, bridges, dams</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>communities</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>cities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>pipelines, electric grid, interstates</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>systems/societies</td>
<td>shipping, air transport</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>global</td>
<td>global climate</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>satellites</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>solar system</td>
<td>UV degradation</td>
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### Table 2  Powers of Ten—Time

<table>
<thead>
<tr>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Unit</strong></td>
</tr>
<tr>
<td><strong>Example(s)</strong></td>
</tr>
</tbody>
</table>
-9 | ns | |
-8 | | |
-7 | | |
-6 | µs | PC clock speeds |
-5 | | |
-4 | | explosive chemical reaction; delay between bomb trigger and detonation |
-3 | msec | |
-2 | | frequency of people through Port Authority of NY and NJ Bus Terminal (i.e., 185,000/day) |
-1 | | |
0 | sec | |
1 | | e-mail delivery time; collapse of WTC (13 sec); HVAC shutdown; fire consumes a room. |
2 | min | decision time to shut flood gates; time for CNN to report USAir 1549 “landing” in Hudson. |
3 | hr | plume dispersion; time to pull everyone to shore from Flight 1549 (21 min.); partial evacuation of South Tower WTC on 9/11 (123 min.) |
4 | day | electric power outage NYC 14 Aug 03 (72 h); recommended family survival supplies (72h) |
5 | wk | residence time of water in NYC system (5 days); concrete curing (90% @ 3 wks) |
6 | mo | rebuild of MacArthur Maze (26 days); FIATECH fast permitting |
7 | year | current building permits; power transformer replacement (24 months) |
8 | decade | lawsuits from WTC (>10 yr); U.S. Interstate Highway System (1956) |
9 | century | Woolworth Building (1913); NY Subway (IRT; 1904); Brooklyn Bridge (1883); LIRR (1834); FDNY (1648) |
10 | millennium | Roman aqueducts (312 BC); Egyptian pyramids (2600 BC) |

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### Table 3  Powers of Ten—People

<table>
<thead>
<tr>
<th>Exponent</th>
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</thead>
<tbody>
<tr>
<td><strong>Common Unit</strong></td>
</tr>
<tr>
<td><strong>Category</strong></td>
</tr>
<tr>
<td><strong>Example(s)</strong></td>
</tr>
</tbody>
</table>
0 | | individual | you |
1 | tens | group | |
2 | | this conference | |
3 | thousands | community | Population of Manhattan pre–Henry Hudson |
4 | | | |
5 | | town | |
6 | millions | city | |
7 | | | NY Metro (22M) |
8 | | nation | |
9 | billions | | |
10 | | world | |
A Roadmap to Resiliency

To achieve the vision of a resilient America, we must commit to a sustained effort across geographic, political, economic, infrastructure sector, and presidential administration boundaries. We must evolve our thinking, investment strategies, and infrastructure to a vision of a strong, resilient America in a complex, dynamic global economy and global society. We must summon the political and social will to pass the laws and appropriations to effect change. But before we commit to this course, we need a blueprint, one whose details will require a national debate on priorities, studies to project cost/benefit ratios, and a consensus among a broad cross-section of politicians, corporate executives, civil servants, educators, and—most importantly—citizens.

Leadership at the highest levels is required. A vision not unlike Eisenhower’s for the Interstate Highway System is required. At the same time, practitioners need to rethink their roles and contribute to the long-term vision through redefining our roles, designing for multiple uses, balancing retrofits and new construction, and approaching our professions through new paradigms.

Redefining the Roles of our Disciplines. A recent article in a trade magazine makes an impassioned plea for better integration of engineers into the overall homeland security critical infrastructure protection architecture, as shown in Figure 3. While this plea goes a long way toward exhorting engineers to think more broadly about their role in infrastructure resiliency, it does not go far enough, especially in the areas of protecting all four threat categories.

The historic channeling of scientists and engineers into specific disciplines and perspectives is a microcosm for the larger societal tendency to isolate disciplines. I was educated as a chemist, where I went into the “Chemistry Building” and went to chemistry meetings. Early in my career, I realized how important interdisciplinary approaches are to solving problems. This early impression has not only remained but intensified through my career as our world has grown more complex, global, and fast.

In addition to just thinking more globally about our disciplines, there are techniques to guide us toward optimal professional behavior.

Assessing Trends and Initiatives. An emerging technique for assessing new trends and initiatives is Positive Deviance. This is an approach to personal, organizational, and cultural change based on the idea that every community or group of people performing a similar function has certain individuals (the “positive deviants”) whose special attitudes, practices, strategies, and behaviors enable them to function more effectively than others with the exact same resources and conditions. Because positive deviants derive their extraordinary capabilities from the identical environmental conditions as those around them, but are not constrained by conventional wisdoms, positive deviants’ standards for attitudes, thinking, and behavior are readily accepted as the foundation for profound organizational and cultural change.

In practice, this change includes methodologies and technologies for:

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• quickly identifying the positive deviants,
• efficiently gathering and organizing the positive deviant knowledge,
• motivating a willingness in others to adopt the positive deviant approaches,
• sustaining the change by others by integrating it into their preexisting emotional and cognitive functions, and
• scaling the positive deviant knowledge to large numbers of people simultaneously.

Therefore, the general idea is to identify the cohorts who “get it” and do the right thing, then, amplify this positive deviance.

There are stunning recent examples of this kind of thinking and subsequent action. General Russel Honoré was responsible for coordinating military relief efforts for Hurricane Katrina-affected areas across the Gulf Coast.15 His positive deviance is credited with turning around the response efforts after prior failures. His direct, hands-on management style created great visuals as he directed soldiers to put down their weapons and focus on the rescue mission. Honoré made headlines nationwide when he told a reporter not to get “stuck on stupid”16 in reference to a question about the government response to Hurricane Katrina when he thought the public should focus on preparedness for Hurricane Rita.

Less flamboyant, but equally impressive as a positive deviant, Admiral Thad Allen was initially assigned to “help bail [FEMA Director Michael Brown] out.”17 Four days later, he assumed full command of the search-and-rescue and recovery efforts, a post he held from 9 September 2005 to 27 January 2006.18

When he took over the Katrina response, Allen says he relied on a “bias for action,” the practice of moving, not endlessly deliberating. Within 24 hours, he and Honoré set up a planning group that would soon meet on the Iwo Jima. Each day, the two would deliver a report on what they hoped to do the next day to New Orleans Mayor Ray Nagin and Louisiana Gov. Kathleen Babineaux Blanco. Of course, decisions made quickly can have massive consequences—something Allen had experienced years earlier, in 1999, when he ordered his charges to bring 5-year-old Elián Gonzáles onto U.S. soil after he was told the youngster was hypothermic. Even though the Cuban boy’s presence ignited a custody battle, Allen says he never regretted that decision. “You develop a battle rhythm in these moments,” he says.19

The post-Katrina Vietnamese experience embodies positive deviance:20

There has been a growing interest among social science scholars to study Vietnamese Katrina evacuees, who were initially and disproportionately among the first to return and to have rebuilt their ethnic community.

Today, 45 of the 53 Vietnamese American-owned businesses concentrated in a commercial area are back, and over 90 percent of Vietnamese residents have returned to Village de L’Est. In comparison, fewer than 50 percent of the Village de L’Est African Americans have returned. …

My field survey does reveal that then as now Vietnamese Americans when faced with catastrophes seem to take the attitude of “nowhere to go but up.”

However, the actual road to recovery will no doubt be influenced by class and

15 http://en.wikipedia.org/wiki/Russel_L._Honor%C3%A9
16 http://www.youtube.com/watch?v=QVBY_SqzHtI
17 Josh White, Coast Guard’s Chief of Staff To Assist FEMA Head Brown, Washington Post, Wednesday, September 7, 2005; Page A23.
18 http://en.wikipedia.org/wiki/Thad_Allen
19 Angie C. Marek, Always Ready for the Storm, U.S. News & World Report, posted 10/22/06.
religion. For example, more than the majority of the survey’s respondents do not think they will fully recover from Katrina. And while they may not have a strong cohesive social network as those associated with the Mary Queen of Vietnam Catholic Church, they are connected to variety of both community and government resources. These resources, particularly the latter, may be quite effective in making “nowhere to go but up” a reality.

Another emerging case study to watch under the lens of positive deviance: Masdar City, UAE, which is being designed to rely entirely on renewable energy sources, be totally sustainable and have a zero-carbon footprint. A success here would inspire innovation in new construction as well as renovations of existing cities.

Positive deviant thinking and attitudes are needed to identify innovative approaches that can revitalize our aging infrastructure, and create resilience.

**Multiple Use Attributes.** We now face homeland security problems of incalculable complexity that demand interdisciplinary, interorganizational, and multinational approaches to solution. One of these is resiliency of our infrastructure. In the first half-decade of homeland security, we have focused on critical infrastructure protection looking primarily at prevention of terrorist attacks and catastrophic natural disasters. While these are important issues for America, they must be put in context with the dual use of making our critical infrastructure resilient against the normal operational foibles, economic hiccups, and snafus. Multi-use facilities make economic sense. Furthermore, when infrastructure has multiple uses, at least one is often routine, so the system is constantly being exercised and does not need to be “stood up” in time of crisis. Dual use keeps operators on their toes, averting the inevitable complacency of waiting for a catastrophic event to occur.

**Retrofit vs. New Construction.** Retrofitting existing infrastructure can extend life, upgrade security, and otherwise enhance structures at a fraction of the cost of replacement. For example, retrofitting cable-stayed and suspension bridges with blast-protective materials has been performed on many key bridges and is the subject of ongoing S&T research, using the expertise of the Engineer Research and Development Center of the U.S. Army Corps of Engineers.  

The Tappan Zee Bridge spans the Hudson River for 4.9 km with 7 lanes of traffic and is a critical component of the region’s transportation infrastructure. “There’s not much monumental about the Tappan Zee. Constructed on-the-cheap between Rockland and Westchester Counties and opened in 1955, it is a mess: overloaded, poorly engineered, in chronic need of extensive maintenance, and potentially dangerous. It is well-known for commuting surprises like an epidemic of “punch-throughs”—holes in the roadway where a chunk gives way and you can see the river below. Planning for a replacement has proceeded for many years and currently includes commuter-train tracks and lanes for high-speed buses.

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21 Mimi Hall, *Effort underway to protect bridge cables*, USA TODAY, September 14, 2007. Image of Sunshine Skyway (Fl) used with permission.


While retrofit has its place and can address specific deficiencies, new construction provides an opportunity incorporate resiliency into the conceptual and as-built designs. Designers must balance factors such as construction costs, operational costs (energy efficiency), habitability, rentability, safety, adherence to codes, and aesthetics. Security and resilience must be factored into the design considerations from the very beginning.

**Architecture.** Evolving from current practices and current as-built structures to a future ideal requires careful planning and strong will to architect appropriate solutions. This requires risk analysis, threat analysis, capacity projections, use projections, and crystal-ball ing changes in technology.

Specific examples:

- resilient transportation logistics
- robust power grid
- secure, reliable communications and data that benefit business, finance, intelligence, education, and, indeed everyone.
- disaster infrastructure that can evolve from meeting basic survival needs to temporary structures and systems that are livable, pleasing, and humane. Too often, refugee camps and temporary housing are sterile with a low livability factor.
- preplaced assets; for example, “How much is enough with respect to redundant infrastructure?”
- preparedness decisions; for example, “How Clean is Clean?” as we remediate WMD contamination, mold, and other contaminants that people can be exposed to.
- innovative manufacturing technologies
- uniform, consensus-based standards and codes.

In the aftermath of Hurricane Katrina, FEMA provided 143,123 families with temporary housing units (travel trailers, park models and manufactured homes) across the Gulf Coast. FEMA partnered with state, local, and voluntary organizations to identify housing gaps, track the resources of various agencies, and ensure a comprehensive approach to transitioning occupants to more suitable long-term housing options. Plagued by formaldehyde contamination, the “Katrina Trailers” have been roundly maligned. About 4,600 remained occupied in early May 2009 as a May 30 closure date loomed. FEMA’s attempts at moving residents to permanent housing have met resistance. These housing issues are entangled with economic, health, age, and “strong racial and class differences.”

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24 Myths & Facts about FEMA Housing Following Katrina, Release Date May 26, 2008, Release Number FNF-08-046. Image used with permission.
25 Richard Fausset, Post-Katrina trailer residents fearful as eviction day looms, Los Angeles Times, May 6, 2009.
26 Shaila Dewan, Leaving the Trailers: Ready or Not, Katrina Victims Lose Temporary Housing, New York Times, May 8, 2009. The deadline was pushed back in late May as hundreds of people remained in their trailers.
Examples of Challenges and Opportunities

Rethinking our Water Systems. 28 Water supply, treatment, sewage systems, and discharge of treated wastewater are an increasing issue in America as population growth and affluence increase demand. Across the world, more than a billion people lack access to clean water and sanitary defecation. 29 An innovation posed by an official from Nevada would be to find a way to “convert” flood water to useful water in parched regions. Are there radical new approaches to how to store/move water? 30

A Resilient Electric System. America uses a lot of electricity. 31 Smart grid is a loose term for modernization of electricity from generation through transmission and distribution to the user. A smart grid uses advanced digital technology to save energy, reduce cost, and increase reliability. In addition, features of Smart Grid can reduce carbon footprint and promote energy independence. From a homeland security perspective, it has the potential to improve the resilience of the grid.

Then President-elect Barack Obama proposed legislation that included doubling alternative energy production in the next three years and building a new electricity “smart grid” 32 and subsequently appointed a national coordinator for the effort.

The United States at Night. 3 Obtaining this image from satellites was possible only by America’s multibillion-dollar space program over 4 decades. The infrastructure it shows represents perhaps a thousand-fold greater investment.

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28 images from PlaNYC.
30 Patricia Mulroy, General Manager, Southern Nevada Water Authority at a rollout event for Memo to the President: Invest in Infrastructure for Long-Term Prosperity, Brookings Institution, Washington, DC, 12 January 2009.
31 For the map image; Credit and Copyright: NOAA/ NGDC DMSP Digital Archive.
Xcel Energy, a Minneapolis-based power utility, and several partners are demonstrating SmartGridCity, the country's first city-scale smart grid, in Boulder, Colorado. Xcel's $100 million program integrates technologies that give both an energy provider and its customers more control over power consumption. Sensors in transformers, smart meters, and fiber-optic communications provide real-time data that allows power stations to adjust the electrical supply, detect failing equipment, and prevent overloads. Consumers, through a Web-enabled control panel in their homes, can adjust their energy consumption for economy—for example, by time-shifting appliance use automatically to reduce power use during peak hours. SmartGridCity’s benefits might include a shift to more clean-power sources; energy conservation; fewer outages; and cost efficiency.  

Particularly at the consumer level, behavioral change requires nudges  through marketing campaigns for compact fluorescent light bulbs (CFLs), “green” appeals, and feedback devices. Ambient Energy Orb is a “groovy little ball that changes color in sync with incoming data”—in this case, an electric meter rate signal. The Orb reminds customers of their instantaneous electric usage and alerts them when demand is high or low. Customers have reduced peak-period energy use by 40 percent.  

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33 Smart Grid Strategy and Vision, Xcel Energy. Image used with permission
Think out of the box. For transportation, we might architect electric propulsion for both passengers and freight, while simultaneously charging the battery of a discrete vehicle. The vehicle could then enter or exit from local streets where self-contained propulsion would be needed. The concept drawing shown here illustrates buses only, but an adaptable mix of buses, cars, and freight vehicles would provide additional capacity and flexibility. The concept has been tested in Denmark, Los Angeles, and Seattle. Cartoons are easy to draw, prototypes only moderately challenging, and enthusiasm from futurologists lavish. The immense technical challenges to full-scale implementation include effective on/off ramps, guideway design and construction, intelligent switching of cars on/off, and effective integration of the systems. The societal challenges are every bit as daunting: securing rights of way, paying for construction and user costs, and supplying the additional electricity. Converting ideas like this to reality is an imposing challenge, but no more so than challenges that Americans have met many times throughout their history.

Standards and Codes. At many levels, standards, codes, and practices will affect our ability to deliver a resilient infrastructure. At the device and component level, there are myriad electrical, physical, communications, and computer standards that ensure proper function, encourage interoperability, and facilitate installation, operation, and maintenance. In the United States, more than 40,000 jurisdictions enforce building codes. Even within these jurisdictions, there are myriad agencies that need to permit construction. I have seen 18 permits posted in front of a home renovation in Greenwich Village, New York City.

Especially since 9/11, construction processes and building codes have evolved for both new structures and renovations to provide a safer-built environment. These objectives need to blend with other forces to not only protect the public but also ensure that America remains economically competitive on the world stage. Clearly, standards and codes can push the national agenda and blend security with green construction, energy efficiency, application of new materials, and adoption of better processes. There is a need to streamline the processes beyond just “fixing the codes,” to an extent that leads to integration of the entire construction industry as discussed immediately below.

Integrated Capital Projects. Current issues such as security, environment, safety, economy, globalization, and changing uses combine to provide opportunities and challenges to the capital projects industry. The companies and professions that plan, design, procure, construct, and ultimately operate critical infrastructure can apply technologies, business practices, and governance to vastly improve the processes.

Integrated business practices will improve business flow during the complex design, permitting, procurement, and construction cycle for a large building, factory, or other structure. One effort to integrate, FIATECH, is a partnership to progress along a roadmap toward highly automated processes that seamlessly integrate people, organizations, and processes to reduce cost and time of these major projects. 40

37 RUF Dual Mode Transportation System, Image used with permission
This roadmap depicts a completely integrated structure composed of nine critical elements and can be thought of as a virtual enterprise for the near-term future:

- Scenario-based Project Planning
- Automated Design
- Integrated, Automated Procurement & Supply Network
- Intelligent & Automated Construction Job Site
- Intelligent Self-maintaining and Repairing Operational Facility
- Real-time Project and Facility Management, Coordination and Control
- New Materials, Methods, Products & Equipment
- Lifecycle Data Management & Information Integration.
- Technology- & Knowledge-enabled Workforce

The potential benefits of integration and automation technology include:

- up to an 8 percent reduction in costs for facility creation and renovation
- up to a 14 percent reduction in project schedules
- repair cost savings ranging from 5 to 15 percent
- significant collateral benefits to homeland security by providing an industry focal point for improving capital facility resilience to external threats.

**Interdependencies.** America’s critical infrastructures and key resources (CI/KR) are the basic building blocks of our society and are critical to our economy, security, and way of life.

The component structures, systems, facilities, and institutions are sophisticated, complex, highly interdependent, and too-often fragile. Increasingly, infrastructure is interconnected via communications, data, transportation, finance, and other linkages that subject one component to stress or failure resulting from problems originating in another sector, often geographically and societally distant. Even simple retail transactions are stymied by power failures when the cash registers do not work and credit card charges cannot be put through. Further interdependencies are illustrated in the discussion on pandemics, below. Threats come from natural hazards, terrorism, and innocent errors. A resilient infrastructure requires robust linkages at the key interconnects. As Americans, we can build and maintain these linkages only after we fully understand the threats and vulnerabilities. Modeling the performance under various disaster scenarios has matured in recent years, but there are significant opportunities to improve the modeling, especially at the granularity needed to address business decisions by individual infrastructure owners or by regions.

**Pandemics.** Interdependence of critical infrastructure is widely recognized, but the extent of the interdependencies and the cascading effects of failures are often unrecognized, seldom quantified, and rarely prepared for. For example, a pandemic could run a 2-year course with 66 percent of the cases in first 6 months and 30 percent of workers sick at any given time and plenty more scared stiff. Absenteeism on this scale leads to failures in production, distribution, and delivery, causing shortages, hoarding, and gas lines. Everything is disrupted in a cascading failure of fuel, food, business, crime (up!), insurance, health

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41 National Infrastructure Simulation and Analysis Center (NISAC), Department of Homeland Security (DHS), Sandia National Laboratories (SNL), and Los Alamos National Laboratory (LANL).
care, energy, agriculture, and education. The collapse in individual sectors leads to systematic collapse. Recovery is stifled by disrupted interdependencies. A major impediment to recovery is the lack of confidence that other parts of the system will recover in sequence to restart various components and relink the production, distribution, and delivery chains. In a hospital, this breakdown of order manifests itself in increased patient loads while there are staff shortages and disruptions in delivery of medical supplies and food, waste disposal, and cash.

On the issue of cash, nearly all of a hospital's income comes from insurance and government payments. If the claims processors are out sick, income will lag and cash reserves will dwindle. If the societal collapse is severe, vendors and employees may demand cash. 42 In 2003, the SARS epidemic struck Toronto with 275 cases and 43 deaths. North York Hospital was the epicenter: 65 staff members contracted the disease; one staff member died. Four thousand employees were quarantined, causing extensive personal hardships. Working under quarantine required changes in management practices, changes in work rules, and an army of a thousand volunteers to run errands for quarantined employees. 43

Preparedness can mitigate the effects of these interdependent infrastructure sectors, especially if key linkages are understood before an event unfolds. Preferred-provider and other agreements can place institutions higher on delivery priority lists. Cross-training personnel can allow better staffing flexibility. Hospitals exemplify the complexity in the preparedness required. Standards of care are an extremely complex issue involving emotional, legal, and clinical issues, among others. The New Jersey Hospital Association has developed Planning Today for a Pandemic Tomorrow, a comprehensive resource that hospitals have been using to guide their preparedness efforts. The resource includes 10 modules that address how to develop effective policies and procedures in critical areas such as Clinical Care, Ethics, Operations, Finance, and Human Resources:

- Communications Planning & Assessment
- Human Resources Planning & Assessment
- Finance Planning & Assessment
- Psycho-Social Planning & Assessment
- Supplies, Logistics, Support Services Planning and Assessment
- Ethics Planning & Assessment
- Legal/Regulatory Planning & Assessment
- Clinical Care Planning & Assessment
- Operations Planning & Assessment
- Leadership Planning & Assessment

**Exit 14.** In New Jersey, “What Exit?” is a shorthand query for, “Where do you live?” The NJ Turnpike (I-95 in its northern half) cuts diagonally across the state, linking New York City (Exit 18) with Philadelphia and Wilmington (Exit 1). The turnpike serves as a major transportation corridor. Exit 14 is in Newark and connects the turnpike with Interstate 78 and other highways. Immediately surrounding Exit 14 are dozens of critical infrastructure elements (Figure 4), including the Newark Airport (EWR), the Port of Newark/Elizabeth, freight rail, passenger rail, pipelines, and hundreds of businesses.

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43 A Journey from Crisis through Transformation + Renewal, Bonnie Adamson, CEO-N York Hospital, Toronto [www.nygh.on.ca](http://www.nygh.on.ca), ibid.
DHS and the NJ Office of Homeland Security and Preparedness are conducting a study of the “Port Interdependency, Resiliency, and Resumption of Trade Plan: Port of NY&NJ,” which will examine the interdependencies of this complex, tightly interconnected area and develop recommendations for changes that will increase resiliency. The study team is working closely with the component infrastructure owners, such as the Port Authority of New York and New Jersey.
Models for Our Future

Many local, regional, and national efforts are underway, pushing toward a resilient infrastructure. Some are more direct than others. President Obama’s statement in the introduction to this paper quite directly calls for a different, more resilient future. Below, New York’s plan for 2030, a national coalition, and a National Academies of Science report provide three examples of others’ thinking.

PlanNYC: A Greener, Greater New York

PlanNYC: A Greener, Greater New York is a design for the sustainability and resiliency of New York City, with a vision for the city over the next 25 years. The plan sets priorities for the city’s infrastructure, based on three overarching assumptions:

- NYC will be getting bigger (much bigger).
- NYC’s infrastructure will be getting Older. (And it’s pretty old to begin with).
- NYC’s environment will be at risk (and that’s not a risk worth taking).

Selected specifics

- Congestion Pricing 44
- Upgrade transportation infrastructure (additional subway capacity, commuter rail, express bus...)
- Improve water supply and distribution.
- Plant 1 million trees.
- Add 1800 miles of bike paths.
- Revise building codes for such endpoints as green parking lots and blue roofs. (Retain rain water until sewers can handle the flow.)
- Reduce electric bill from $5 billion \((5 \times 10^9)\) to $3 billion \((3 \times 10^9)\) by 2015.
- Clean up water, air, and the environment.

Infrastructure Impacts. These climate changes will have consequences for New York City’s critical infrastructure.

Temperature-related impacts may include

- increased summertime strain on materials
- increased peak electricity loads in summer and reduced heating requirements in winter.

44 This was proposed to the NY State Legislature and rejected in 2008.
Precipitation-related impacts may include:

- increased street, basement & sewer flooding
- reduction of water quality.

Sea level rise-related impacts may include:

- inundation of low-lying areas & wetlands
- increased structural damage & impaired operations.

**National Implications.** PlanNYC focuses on New York but can have broader implications:

- Interdependencies are universal. We cannot afford to address New York or the nation in a piecemeal manner.
- This NYC-centric effort can serve as a template and for national visionary planning on an integrated and massive scale.
- There are opportunities to influence decisions that improve homeland security while also meeting PlanNYC goals.
- There are lessons about public communications, scientific involvement, grass-roots volunteerism, and political negotiations that have implications for other cities, states, and indeed the federal stage.
- We need to focus beyond the primary impacts of population, infrastructure, and environment to questions about secondary and tertiary impacts, such as whether nor’easter storm frequency or intensity will increase.
- As PlanNYC and other integrated planning efforts mature, we need to examine the underlying assumptions (such as how many people come to work) and recraft goals to a truly 21st century vision and not merely a tweaking of our prior investments.

**A National Coalition**

“Building America’s Future” 45 will serve as a repository of best practices on infrastructure funding issues and become a think tank focusing on emerging infrastructure issues. The organization will advocate a new era of strategic planning, economic analysis, accountability, and rigorous performance standards for U.S. infrastructure investment. It will also advocate infrastructure policy that is forward-thinking and comprehensive in scope, yet grounded in the need for environmental sustainability, lower carbon emissions, and reduced U.S. dependence on foreign oil.

**National Academies Report**

In early 2009, America’s National Academy of Sciences issued a report, *Sustainable Critical Infrastructure Systems: A Framework for Meeting 21st Century Imperatives*. 46 The findings in the report are consistent with the arguments here and are compellingly presented. A key section of the “Findings” section is quoted below (bold emphasis added):

> At a time when many have called for infrastructure renewal in some form and have suggested billions or trillions in investment, there is an important opportunity to fundamentally reexamine the purposes and value of critical infrastructure systems and of the decision-making processes used for investing in them. While daunting, this reexamination can yield a new paradigm from which to develop practical, cost-effective solutions to complex challenges and help meet the needs

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45 California Governor Arnold Schwarzenegger, Pennsylvania Governor Edward Rendell, and New York City Mayor Michael Bloomberg are key founders of the organization. [http://www.investininfrastructure.org/](http://www.investininfrastructure.org/).

of future generations. Some of the ingredients needed to create a new paradigm are available today. Research has yielded technologies for monitoring infrastructure condition and performance, new materials for constructing and repairing infrastructure components, and new knowledge about the interrelated nature of water and wastewater, power, transportation, and telecommunications systems. Self-diagnosing, self-healing, and self-repairing systems can be designed to provide for greater resiliency, fewer long-term service disruptions, and lower lifecycle costs. An array of financing mechanisms, strategies, plans, and approaches to infrastructure renewal that offer new ways to provide for essential services has been developed through local, state, and regional initiatives.

To date, however, infrastructure-related technological advances, plans, approaches, and community-based initiatives have been ad hoc in nature, often focusing on one issue, one type of system, or one set of solutions. Lacking a national vision or strategy for critical infrastructure renewal and concentrating on single projects, technologies, financing mechanisms, or narrowly defined objectives, ad hoc efforts run the risk of underutilizing or wasting scarce resources and increasing the probability of serious, unintended consequences. A framework is needed to structure these efforts so that ongoing activities, knowledge, and technologies can be aligned and leveraged to help meet multiple national objectives. The essential components of the needed framework are as follows:

- **A broad and compelling vision** that will inspire individuals and organizations to pull together to help meet 21<sup>st</sup> century imperatives by renewing the nation’s critical infrastructure systems. Such a vision would focus on a future of economic competitiveness, energy independence, environmental sustainability, and quality of life, not a legacy of concrete, steel, and cables.

- **A focus on providing the essential services involving water and wastewater, power, mobility, and connectivity**—in contrast to upgrading individual physical facilities—to foster innovative thinking and solutions.

- **Recognition of the interdependencies among critical infrastructure systems** to enable the achievement of multiple objectives and to avoid narrowly focused solutions that may well have serious, unintended consequences.

- **Collaborative, systems-based approaches** to leverage available resources and provide for cost-effective solutions across institutional and jurisdictional boundaries.

- **Performance measures** to provide for greater transparency in decision making by quantifying the links among infrastructure investments, the availability of essential services, and other national imperatives.

An important first step in creating a new paradigm is to bring together those who have an essential stake in meeting 21<sup>st</sup> century imperatives and who are already involved in sustainable infrastructure efforts. They include infrastructure owners, designers, engineers, financiers, regulators, and policy makers, as well as ecologists, community activists, scientists, and researchers. Working within the framework, experts in such areas could begin to identify a full range of new approaches, technologies, and materials for providing services involving mobility, connectivity, water, wastewater, and power to meet multiple objectives. They could also identify new approaches to the decision making, finance, and operations processes related to critical infrastructure systems. The results of such a gathering could serve to initiate a longer-term, collaborative effort to develop a vision that would provide guidance for developing concepts and objectives for the nation’s critical infrastructure systems and then to identify the policies, practices, and resources required to implement them. **The results could be critical infrastructure systems that are physically resilient, cost-effective, socially equitable, and environmentally sustainable for the next 50 years.**

**Concepts**

As New York and by extension, the nation, addresses PlanNYC, we need to consider many alternatives and apply science and technology now to assess the efficacy of these and many other options:

- Reduce flooding impact by moving boilers and electrical out of basements.

- “Waterproof” hospitals, nursing homes, and other critical infrastructure with a sacrificial first floor or by sheathing the floodable elevations.

- Construct flood gates across Verrazano Narrows and two other ocean-accesses to retard storm surge.

- Raise the street level like Chicago\(^{48}\) and Galveston\(^{49}\) did in the 1850s–1860s and 1900s, respectively.

- Plan big, but build incrementally. For example, a protective storm-surge barrier that incorporates access, commerce, ecological continuity, ocean hazards protection, and inland value could be constructed in phases that are timed and adjusted as the threat projections unfold. This would also allow investment to be spread over many decades.\(^{50}\)

- Consider high-speed, automated freight rail to deliver goods and remove much of the freight from the highways and freight air. This national system would have spurs reaching into metro areas such as New York. Currently, New York City is not served by freight rail; all incoming goods and outgoing exports and waster must be transported by other means.\(^{51}\) Forecasts indicate that the demand for goods in the metropolitan region will grow roughly 70 percent by 2025. Just the cross-harbor tunnel to connect Brooklyn and Long Island with the mainland is projected to cost from $4.8 billion ($4.8 \times 10^9$) for the single tunnel system to $7.4 billion ($7.4 \times 10^9$) for the double tunnel system.

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50 Personal communication, John Voeller, OSTP, April 2009.

51 [New York City Economic Development Corporation (NYCEDC)](http://en.wikipedia.org/wiki/Raising_of_Chicago), in coordination with the Federal Highway Administration (FHA) and the Federal Railroad Administration (FRA), has completed the preparation of a Draft Environmental Impact Statement (DEIS) for the Cross Harbor Freight Movement Project. The evaluation process, which began in 2002, involved the rigorous examination of the alternatives based on the engineering requirements; capital, and operating costs; environmental impacts and benefits; transportation issues; and opportunities and economic benefits. Image from Cross Harbor Web site.
• Rail may not be the only solution. Short-seas shipping may provide alternatives. Maglev, pneumatics, or even conveyor belts may win out once an objective examination of the various options is conducted.

• Use a certification system for resilient structures and systems along the lines of, or in collaboration with, the Leadership in Energy and Environmental Design (LEED) certification system that “measures how well a building or community performs across all the metrics that matter most: energy savings, water efficiency, CO₂ emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts.” ⁵² Resilient Certification would reward those who build or renovate infrastructure to maximize the key metrics of resilience.

• In the near term, incorporate resiliency concepts into implementation of “PS Prep” (Private Sector Preparedness Accreditation & Certification Program). ⁵³ This “9/11 legislation” stipulates that the program should, among other things, provide a method to independently certify the emergency preparedness of private sector organizations, including disaster/emergency management and business continuity programs.

• Take advantage of wind power, using urban wind screws with a vertical profile fitting within urban canyons. These wind screws would use the turbulent winds and updraft from the urban heat island. The electric generation might be combined with pumped storage of water to the top of high rises, for subsequent use and/or power generation. Or, a turbine might double as an escape route—an incredibly outsized slide like the kind we used on playgrounds. ⁵⁴ Or, a turbine might double as an escape route—an incredibly outsized slide like the kind we used on playgrounds.

• **Green roofs** with plants to absorb water are well-established; **blue roofs** that simply hold the water until the sewer systems can handle it or for grey-water uses would also substantially reduce impacts on water and sewage systems.

• Antimicrobial coatings can reduce infections in hospitals, locker rooms, and other confined areas. BioShield ⁷⁵, for example, can kill viruses, mold, bacteria, and other microbes. ⁵⁵

• Permeable pavement allows surface water to seep back into the earth after being filtered of many pollutants, reducing the volume of storm water runoff that can cause flooding. If the runoff enters a sanitary sewer, it taxes the capacities of water treatment facilities; if it is discharged into a waterway, it carries pollutants.

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⁵³ The Implementing Recommendations of the 9/11 Commission Act of 2007 (Public Law 110-53—Title IX, Section 524) was signed into law on August 3, 2007. Section 524 calls for the creation of a voluntary business preparedness accreditation and certification program.

⁵⁴ Image is a helical turbine, posted 24 May 2008, whose axis points to the zenith. It sits atop a building that is shaped to bring more wind to the turbine Used with permission from Frank Castiglione.

⁵⁵ The coating is spray-applied and protects for more than 30 days. The molecule is an organosilane quaternary amine that copolymerizes after application to a surface; the free end conforms to a spike. The positively charged amine moiety attracts negatively charged microbes that then become impaled and ruptured. It is also used as a coating in air filters for vehicle and aircraft cabins. Image reproduced with permission.
Electrochromic glass is coming on the market. It consists of ordinary float glass sputter-coated with several layers of thin films. SageGlass® glazing is an example:

When voltage [less than 5V DC] is applied to these layers in their “clear” state, they darken as lithium ions and associated electrons transfer from the counter electrode to the electrochromic electrode layer. Reversing the voltage polarity causes the ions and associated electrons to return to their original layer, the counter electrode, and the glass untints. When the electrochromic coating darkens, the sun’s light and heat are absorbed and subsequently reradiated from the glass surface—much the way low-emissivity glass also keeps out unwanted heat. 56

The product has both privacy and energy-efficiency attributes. In the concept of dual use, one could consider the following additional adaptations with additional development:

- **Privacy**—There are certain high-value rooms or buildings where it may be important to automatically make the glass go opaque.
- **Blast resistance**—A major hazard during an explosion is flying debris, especially glass fragments. There are several laminated glass options out there with varying levels of blast resistance.

### S&T Opportunities and Obligations

The opportunities for America to improve its resiliency depend on, among other things, implementing new technological solutions. The scientific and engineering communities can infuse scientific approaches as well as new technologies into other ongoing programs. DHS S&T can contribute through modeling interdependencies, logistics modeling, modeling the intermodal operations, and demonstrating dual use. Basic science in enabling technologies will pay off in sensors, protective measures, advanced materials, nanoscale coatings, and multiple other unforeseen areas.

- Baseline “facts” about the dismal shape of America’s infrastructure need an **independent validation** and an analysis of alternatives that goes beyond the “repair or let it fall apart” dichotomy.
- **Provide better information.** Instrumented structures (Smart Buildings) can monitor health, identify trends, and predict failure. Data will become ever cheaper as sensors and communications become more efficient. Mountains of data are of no use until we convert the data to useful information that enables decisions, reduces uncertainty, and provides warnings or assurances.
- **Materials science** will continue to produce new structural, coating, lighting, photovoltaic, and sensor materials.
- **Engineers and inventors** will apply novel materials and novel construction concepts to provide better, faster, cheaper structures.
- We are just beginning to understand **interdependencies.** With better understanding and models, we can prioritize activities, schedule logistics, and call upon precious resources from all sectors during both crisis and ongoing operations. We also need to know better

how to rebuild, rejuvenate, and repurpose as-built infrastructure to accommodate future capacity and changing modalities. A key interdependency is intermodal transportation and shipping.

- **Risk Assessment** is pervasive in the science, homeland security, finance, insurance, commercial, and health care disciplines and many others. Different disciplines assess risk differently, partly because of differing priorities, but also because of poor assumptions and models. The science community can work to both improve the science of risk assessment and harmonize the different communities.

- **Risk education** is needed at all levels so that society can address decisions that involve deferred risks or payoffs, including global climate mitigation, extra capacity for anticipated future needs, and deferring payments to the next generation. We also need to make risk-informed decisions with complex risk factors such as fire safety, livability, hurricane-proofing, financial return, terrorism, environmental impact, human exposure, structural life, initial cost, and ongoing operational expenses.

- **Adaptive systems** can learn to react rapidly to changing conditions and can operate under conditions of high uncertainty. For example, transportation networks can be trained to adapt to congestion, accidents, or outages. Adaptive electric network management can level power loads and prevent cascading outages.

- **Assess assumptions.** Many decisions about next-generation infrastructure assume that people will continue to come to work as before, continue to live where they have, buy similar goods, consume information the same way, and use transportation for travel and shipping about as before. Some assumptions are valid, some not. Science-based scenario modeling can test the validity of assumptions.

- **Advance future projections** and predictions to understand and thereby reduce uncertainty. Ongoing societal changes such as redistribution of the workplace can radically impact future projections. We need to move beyond current practices that are, in many cases, mere guesses. Can we develop robust models that can reliably project the impact of future issues such as changes in travel as we mature video teleconferencing, shift populations, and change work habits? Although some technologies will apply in the future, the needs, constraints, and rules will be quite different. If well-understood, we can exploit these future demands to pursue innovative solutions in directions we have never before considered. Albert Einstein summed it up nicely: “We cannot solve our problems with the same thinking we used when we created them.”

- **Standards** in so many areas are key to interoperability, economic efficiency, stable business models, and technological advances. We need to improve and unify building codes and permitting processes, among other standards. Standards and enforcement are also keys to protecting against unintended consequences of better, faster, cheaper materials and construction methods that may fail, emit toxic gases, or be excessively combustible, for example.

- **Governance models** are too-often rooted in centuries-old laws and customs and do not address the needs of the 21st century. In particular, we need to think, plan, and govern across state and other boundaries because disasters do not respect political boundaries. We need to replace competitive, zero-sum-game with partnership behavior. We need to modernize financing, cash flow, and project management processes. Understanding and exploit-

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57 A notable example is the ceiling collapse at Boston’s Big Dig, caused by a failure of an epoxy used to hold the bolts into concrete.

58 The infamous formaldehyde in the FEMA travel trailers used as temporary housing after Hurricanes Katrina and Rita is just one example of “sick buildings” caused by inferior or improperly applied materials.
ing the value chain can ensure that all interests are balanced: users of commercial facilities typically have no say in the design, construction, and security of commercial facilities, except through standards, codes, and government regulation. Science can provide better tools to assess and predict regional resilience issues.

- **Financing models** can be improved to change budgeting processes; allow governmental savings accounts for anticipated and unanticipated maintenance and capital projects; better understand the impact of user fees, tolls, and gas taxes; and examine the impact of current and future pricing policies. For example: General thinking is that water is now grossly underpriced to the user. Is this a leverage point for shifting demand and usage? Also, would governmental savings accounts induce better planning and future-thinking? How can we model these changes without resorting to trial-and-error legislation?

- **Manufacturing and business models.** 21st century infrastructure will require 21st century manufacturing, a more nimble workforce, consensus-based standards, performance-based codes (not prescriptive codes), and tempered liabilities. The FIATECH model discussed above provides a roadmap for near-term improvements; we can build on this type of thinking for future generations’ integrated capital projects and systems architecture. Business scientists can help move our construction, materials, engineering, architecture, and logistics industries toward a lean-and-mean solution.

### Partnership for Resilient Infrastructure

We can design, build, maintain and leave for our grandchildren a resilient America. It will not be easy or cheap. Among the changes needed are new partnerships across disciplines. To achieve the goals discussed here, we need active leadership, participation, and collaboration from all stakeholders:

- Physical scientists
- Engineers
- Social scientists
- Behavioral scientists
- Economists
- Financiers
- Insurers
- Lawyers
- Inventors
- Planners
- Politicians
- Citizens
- Industries
- Historic Preservationists

We will need to attack entrenched interests and inertial practices with

- correct assumptions
- new industrial approaches
- new companies willing to fight entrenched practices
- faster and more universal standards and codes
- new sensors, controllers, and materials

- integrated solutions
- facts
- compelling risk, liability, and cost analyses
- appropriate, validated models for finance, governance, business, interdependencies, and engineering.

Contributions and out-of-the-box approaches need to come from new directions. For example, designers are not usually considered part of the infrastructure mix, yet…

[Hilary] Cottam is one of a new wave of design evangelists who are trying to change the world for the better. They believe that many of the institutions and systems set up in the 20th century are failing and that design can help us to build new ones better suited to the demands of this century. Some of these innovators are helping poor people to help themselves by fostering design in developing economies. Others see design as a tool to stave off ecological catastrophe. Then there are the box-breaking thinkers like Cottam, who disregard design’s traditional bounds and apply it to social and political problems. Her mission, she says, is “to crack the intractable social issues of our time.”

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Scientists, engineers and others in the science and technology enterprise must work together. More important, we must listen to voices from far-flung disciplines and develop communications pathways that will allow us to partner among the diverse disciplines.

**Conclusions**

This paper presents a vision of America’s future infrastructure that will increase the nation’s resiliency, reap the benefits of improved societal efficiencies, and strengthen America on the world stage. America must develop and implement technologies, processes, standards, codes, and laws that enable the vision. A blueprint is needed that will require a national discourse on priorities and technological assessments that provide solid, compelling evidence for a positive cost/benefit ratio. The issues of governance, integrated planning, finance, and societal prioritization require a discourse among all American institutions and individuals. The scientific community, notably the social sciences, can contribute to ensuring that the discourse is fact-based and that various processes use validated models and calculation techniques.

Traditionally, science and technology have provided a toolbox of new technologies, new materials, new monitoring, better controls, and optimization models. Scientists and inventors will continue to provide new toolbox-advances that will shape the discussion on how we achieve a resilient infrastructure. More important, science and technology can contribute to shaping our blueprint by instilling scientific rigor into the process and engaging with the other sectors that will shape our future. Science’s role in understanding interdependencies at multiple scales, setting standards, examining underlying assumptions, informing decisions with data, envisioning possible future technologies, developing architectures, improving risk assessment, analyzing alternatives, and running scenarios is critical to optimize and rationalize the vision. Science and technology can also contribute to providing 21st century governance, financing, manufacturing, and business models.

Intelligent revitalization and expansion of America’s infrastructure requires innovation on many physical and temporal scales. Scientists and engineers have a voice and a role in shaping this vision. The science and technology community needs to participate in the discourse and provide guidance on the technical, economic, and social possibilities for our future.

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