POLICY BRIEFS SERIES

Toward a Smarter Future: Building Back Better with Intelligent Civil Infrastructure

Smart Sensors and Self-Monitoring Civil Works

Stephen Goldsmith, Betsy Gardner, and Jill Jamieson

SEPTEMBER 2021

HARVARD Kennedy School
ASH CENTER
for Democratic Governance and Innovation

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Executive Summary

The United States needs to build better infrastructure. The current repairs and replacements are disorganized and patchwork, resulting in unsafe, costly, and inequitable roads, bridges, dams, sidewalks, and water systems. A strategic, smart infrastructure plan that integrates digital technology, sensors, and data not only addresses these issues but can mitigate risks and even improve the conditions and structures that shape our daily lives.

By applying data analysis to intelligent infrastructure, which integrates digital technology and smart sensors, we can identify issues with the country's roadways, buildings, and bridges before they become acute dangers. First, by identifying infrastructure weaknesses, smart infrastructure systems can address decades of deferred maintenance, a practice that has left many structures in perilous conditions. Sensors in pavement, bridges, vehicles, and sewer systems can target where these problems exist, allowing governments to allocate funding toward the neediest projects.

From there, these sensors and other smart technologies will alert leaders to changes or issues before they pose a danger—and often before a human inspector can even see them. The many infrastructure emergencies in the U.S. cost thousands of lives and billions of dollars each year, so identifying and fixing these issues is a pressing security issue. Further, as the changing climate leads to more extreme weather and natural disasters, the safety and resiliency of the country's infrastructure is an immediate concern. Sensor systems and other intelligent infrastructure technology can identify and mitigate these problems, saving money and lives.

In addition, intelligent infrastructure can be layered onto existing infrastructure to address public health concerns, like monitoring sewer water for COVID-19 and other pathogens or installing smart sensors along dangerous interstates to automatically lower speed limits and reduce accidents. It can also be used to improve materials, like concrete, to reduce the carbon footprint of a project, ultimately contributing to better health and environmental outcomes.

Finally, addressing inequities is a major reason to utilize intelligent infrastructure. Research shows that people of color in the U.S. are exposed to more pollutants, toxic chemicals, and physical danger through excess car emissions, aging water pipes, and poor road conditions. The implementation and funding of these intelligent infrastructure projects must consider where—and to whom—harm has traditionally been done and how building back better can measurably improve the quality of life in marginalized and vulnerable communities.

While there are challenges to implementing a sweeping intelligent infrastructure plan, including upfront costs and security concerns, all levels of government play a role in achieving a safer society. At the federal level, with infrastructure funding bills being debated at this moment, the government must look beyond roads and bridges and consider that intelligent infrastructure is a *system*: upheld, connected, and integrated by data. Through grants, incentives, and authorized funding, the federal government can effect monumental change that will improve how all residents experience their daily lives. At the state level, budgeting with intelligent infrastructure in mind will encourage innovative approaches to local infrastructure. And on a municipal level, cities and towns can invest in comprehensive asset management systems and training for local workers to best utilize the intelligent infrastructure data.

I. Introduction: The Need to Rebuild American Infrastructure

The U.S. economy relies on a vast network of public infrastructure, ranging from roads and bridges to ports and transit systems, from electrical grids to water systems, from inland waterways to dams and levees, and from public schools to waste management and treatment systems. Since the 1960s, when most of the country's major civil infrastructure systems were designed, the U.S. population has more than doubled. Now, much of the nation's infrastructure is in urgent need of upgrade and expansion as it extends beyond its useful lifespan.

Evidence of America's decaying infrastructure systems is everywhere. While the headlines regularly call attention to devastating failures, such as the 2021 Texas power grid crisis, the Flint water crisis, the 2017 Oroville Dam collapse, or the 2017 bridge collapse on Interstate 85 in Atlanta, the public bears witness to less dramatic failures every day. From a water main breaking every two minutes to American drivers losing nearly 100 hours a year, on average, due to road congestion,1 our aging civil infrastructure imposes large costs on the U.S. economy. In addition to the threat to human safety due to catastrophic failures, inadequately maintained roads, trains, and waterways cost billions of dollars in lost economic productivity.

For this reason, upgrading, modernizing, and expanding civil infrastructure is one of the relatively few policy areas for which there is broad public support, regardless of political identity. As a kitchen-table issue, both sides of the political spectrum have professed enthusiasm for a federal infrastructure bill that would boost government spending to address crumbling roads and bridges as well as other programs. While there have been important differences in terms of the overall size and scope of these proposals, and in how to pay for them, there is also a notable similarity in terms of what is missing. Both sides propose expanded investment to rebuild key components of our collapsing infrastructure, but neither point to the role that intelligent infrastructure should play in replacing our decaying 20th-century assets. Moreover, they ignore the role that data derived from intelligent infrastructure will have in prioritizing future investments, ensuring greater efficiency and cost savings over the life of an asset, or even adjusting design parameters for greater adaptability and resilience.

The United States would benefit from taking a more strategic approach to infrastructure. It must move beyond "repair and replacement" to address the fact that our network of infrastructure assets needs to work together seamlessly as an integrated whole. The country must also look to avoid the pitfalls of the past, ensuring timely maintenance and effective life-cycle asset management while recognizing that our physical and digital worlds have become permanently intertwined. In short, America must not only focus on "building back better" but on "building back smarter" through more technologically advanced infrastructure. Tying any infrastructure plan to increased investment in intelligent infrastructure presents an opportunity for federal, state, and local authorities to invest in a future of continuous and lasting change for the benefit of the public.

II. Defining Intelligent Infrastructure

Broadly speaking, intelligent or smart infrastructure can be defined as infrastructure that integrates digital technology and smart sensors to provide self-monitoring and improve decision making. This drives efficiency and cost savings, reliability, security, safety and resilience, user interaction and empowerment, sustainability, and service quality. Intelligent infrastructure is designed for adaptability and functions on data acquisition, data analysis, and maintenance of the feedback loop. It also operates at higher levels than semi-intelligent infrastructure and often (though not always) involves system-level integration of multiple assets or sub-system components. In brief, intelligent infrastructure uses technology to improve outcomes, well-being, and quality of life.

Intelligent infrastructure incorporates smart sensors with embedded microprocessors and wireless communication links that are fundamentally changing the way we monitor, control, and maintain civil infrastructure systems. While sensors and smart technology are not new, their broadscale integration into civil infrastructure is still in its infancy, despite the ability to transform the way that public works are designed, delivered, maintained, and operated. According to Eulois Cleckley, former executive director of the Department of Transportation and Infrastructure in Denver, Colorado and new director of Transportation and Public Works for Miami-Dade County, "Infrastructure is more than just roads and bridges—it's the ability to leverage all pieces of infrastructure to help manage and maintain it."

This new, massive infrastructure investment would be the first to occur since the widespread application of the Internet of Things (IoT) in the early 2000s;2 IoT refers to the connected sensor networks that gather and send data. IoT changed how objects talk to each other and can change fundamental aspects of how the public builds and uses interconnected assets. Architecting physical infrastructure without architecting its digital properties means we would miss an opportunity to hugely transform and rebuild the foundation of how we live and move people and goods. The necessary components for intelligent, digital infrastructure include sensors but also the support and tools for data collection, storage, and analysis. We include in our definition of digital infrastructure the applications that facilitate continuous improvement.[3]

We also include geospatial infrastructure as a critical part of the digital support system. Advances in cloud computing and GPS positioning support spatial analytics, serving as the critical glue for much of our infrastructure. Advanced GIS systems allow officials and residents to see interdependencies by location. As Michael F. Goodchild and Jack Dangermond wrote in a recent article, "Sensors in the environment are able to create an abundance of time-dependent geospatial data, making time an important element of today's vision of geospatial technology. Similarly, contemporary technology, such as GPS, BIM (building information management), structure-from-motion, ground-based LiDAR, and ground-penetrating radar, has made it cheap and easy to acquire three-dimensional representations of geographic features."[4]

III. Benefits of Intelligent Infrastructure

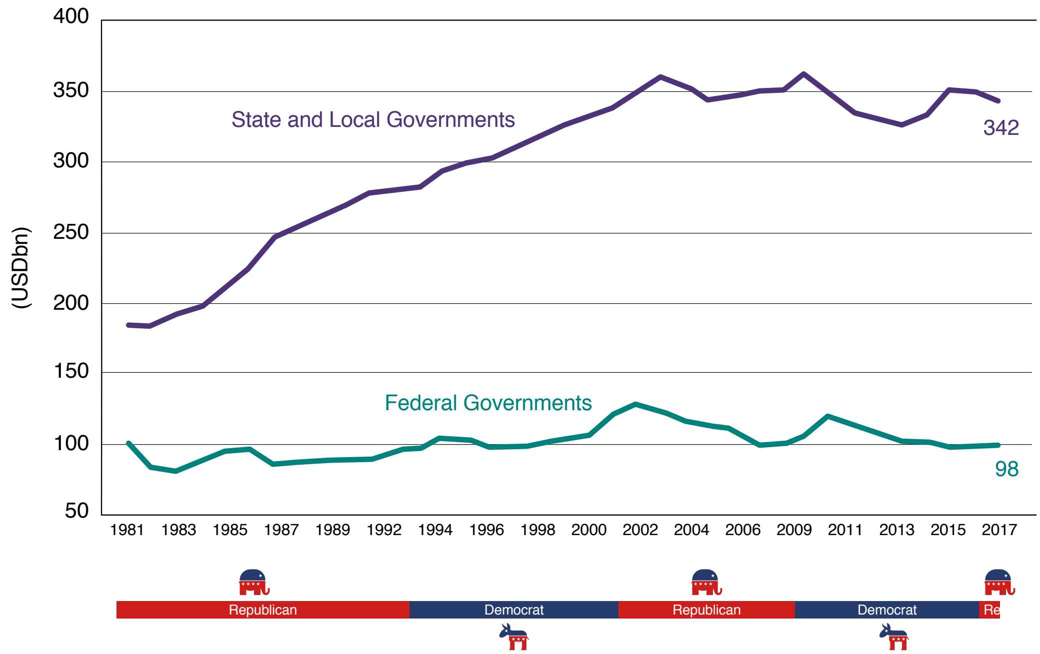
Albert Einstein famously posited, "We can't solve problems by using the same kind of thinking we used when we created them." The demand for civil infrastructure is expanding to new levels as trends in population growth, urbanization, and economic development continue to shift. To address these pressure points, we need to reimagine not only how infrastructure is designed and built but also how it is operated and maintained. While civil infrastructure professionals now effectively aggregate real-world data (computer-aided design or CAD, geographic information systems or GIS, raster and vector, light detection and ranging or LiDAR, photogrammetry, and more) and use that data to quickly create intelligent design models of their projects, so too must we use intelligent infrastructure to make better informed and timelier decisions about maintaining our infrastructure. Failure to do so will result in our infrastructure inventory being perpetually at risk.

1. Life-Cycle Cost Savings through Maintenance Efficiencies

For decades, investment in American infrastructure has been relatively flat, failing to keep pace with rising costs. During the 1950s and 1960s, infrastructure funding primarily supported new construction. Over time, however, the amount of new construction has materially declined as the need for maintenance, rehabilitation, and modernization of aging infrastructure assets has consumed the majority of infrastructure investments. While operations and maintenance funding has increased in nominal terms over the years, funding has not kept pace with the rising costs of maintaining our nation's infrastructure assets.

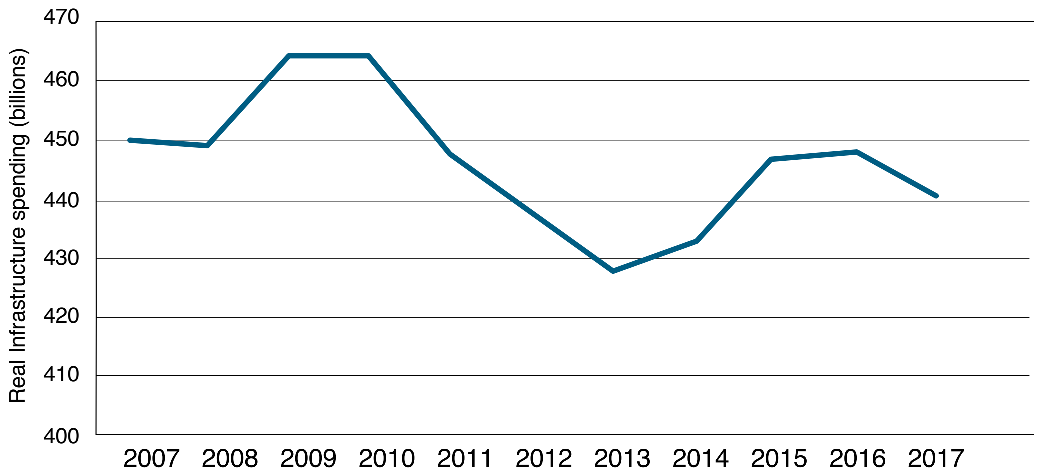
From 2007 to 2017, total public spending on infrastructure fell by $9.9 billion in real terms.[5] While federal, state, and local governments have ostensibly spent more on infrastructure in recent years, the rising cost of materials has reduced their real spending power.[6] As a result, real infrastructure spending nationally fell from $450.4 billion in 2007 to $440.5 billion in 2017. With post-pandemic non-residential construction prices jumping an unprecedented 24 percent,[7] real infrastructure spending is expected to erode further.

Public Spending on Transportation and Water Infrastructure, by Level of Government, 1981–2017



Source: Congressional Budget Office, using data from the Office of Management and Budget, the Census Bureau, and the Bureau of Economic Analysis. Dollar amounts are adjusted to remove the effects of inflation using price indexes for government spending that measure the prices of materials and other imputs used to build, operate, and maintain transportation and water infrastructure.

Unites States Public Infrastructure Spending (in billions of 2017 dollars), 2007 to 2017



Source: Originally published on brookings.edu by Joseph Kane and Adie Tomer via Brookings analysis of CBO data.

B | Metropolitan Policy Program at BROOKINGS

While total public spending fell over the past decade, the amount dedicated to operating and maintaining our aging infrastructure has increased by approximately 9.5 percent.[8] This is not only a natural consequence of our nation's aging inventory of infrastructure assets but also a result of an ever more pressing need to address the nation's massive backlog of deferred maintenance.

The term "deferred maintenance," generally defined as any delayed repairs that can lead to safety hazards and other costs, is a major challenge for policymakers and practitioners at the federal, state, and local levels. Limited funding, coupled with overwhelming need, has resulted in prioritizing only the most urgent maintenance and postponing other critical maintenance activities until either more funding is available or the asset itself is at risk of total breakdown. Unfortunately, this "fix-as-fails" approach to our critical infrastructure is the costliest and least efficient means possible of addressing our nation's critical infrastructure. [9]

Although there is no transparent top-line number that shows the exact scope of our nation's maintenance backlog, its impact is everywhere. Across the United States, there are an estimated 55 million potholes. Thirty-six percent of our nation's bridges require replacement or rehabilitation.[10] And we lose an estimated six billion gallons of treated water per day (14 to 18 percent of the nation's daily water use) due to leaky, aging pipes and outdated systems.[11] While these issues are problematic in their own right, the failure to address them promptly not only puts public safety at risk but also exponentially increases costs.

Simply put, it is bad business to postpone necessary improvements because the associated costs will increase—exponentially—over time. Failure to act in a timely manner to maintain infrastructure assets does not simply move the present burden to future years; it transfers a significantly larger liability to future generations.

Intelligent infrastructure is uniquely well suited to address the issue of deferred maintenance. Continuously monitoring the integrity of civil works, and controlling their responses in real time, can lead to safer infrastructure. This is particularly true for our aging infrastructure, as intelligent infrastructure's capability to prevent structures from reaching their limit states, in addition to the ability to detect damage at an early stage, can reduce the costs and downtime associated with repairing critical damage. Observing or even predicting the onset of dangerous structural issues (such as vibration in bridges) offers an important opportunity for advanced warning, which in turn allows for advanced repair or even removal of that infrastructure before lives are endangered.

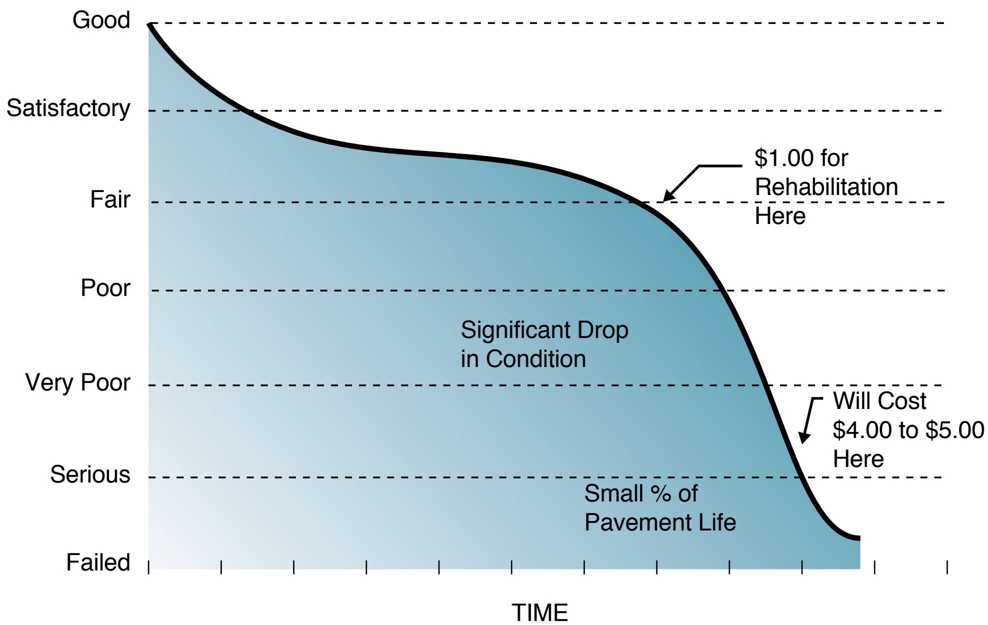
In addition to controlling and monitoring long-term degradation, intelligent infrastructure plays a vital role in facilitating the assessment of critical infrastructure's structural integrity after catastrophic events, such as floods, earthquakes, hurricanes, tornados, or fires. Utilizing traditional inspection practices, this assessment represents a significant expense in terms of time and money. Instead, intelligent infrastructure can provide real-time analytics on a broad range of infrastructure assets, thereby accelerating recovery times.

In short, intelligent infrastructure can enhance safety and reliability while also reducing maintenance and inspection costs. Some recent examples of the use of smart sensors for critical infrastructure are provided below.

A. *Sensor-Equipped Smart Pavement*

Smart pavement is an exciting concept that promises to revolutionize the building, usage, and funding of asphalt roads everywhere. Illustrating the above points, the graphic below shows the extent to which pavements deteriorate over time and suggests that there is a cost-minimizing point of intervention before the pavement deteriorates too much to repair. Research from Michigan State University suggests that for every $1 spent on preventive pavement maintenance, there is a savings of $4 to $10 on rehabilitation.[12]

Typical Pavement Life-Cycle Curve



Source: Federation Avaiation Administration (FAA) 2010

To assess the potential of smart pavement in the real world, the Federal Highway Administration (FHWA) developed and deployed a series of self-powered wireless sensors capable of detecting damage and loading history for pavement structures. In this study, the sensor network collected strain data, which was then "retrieved locally using either a manually operated or truck-based RFID (radio frequency identification) reader."[13]

The FHWA sensor trial demonstrated the many ways in which smart pavement can benefit road operators and the public. For instance, during the trial, Department of Transportation (DOT) engineers used remotely accessed road data to make informed decisions about future maintenance and replacement schedules before the damage was visible at the surface. This demonstrated how reduced equipment deployment can yield significant savings. Furthermore, access to sensor-equipped smart pavement would allow transportation officials to make evidence-based decisions as to priorities and products, including which paving products perform best in their jurisdictions.

Sensor-equipped smart pavement provides data and insights that could promote a more proactive approach to managing pavements, so agencies know about potential pavement damage as early as possible, before it's visible.[14] This could also help resolve issues around equity, as anonymized data could drive project prioritization, thus putting all communities on equal footing.

Indeed, sensor-equipped pavement is not only useful for lowering maintenance costs but also can reduce initial construction costs. At Purdue University, Luna Lu, the American Concrete Pavement Association Professor and founding director for the Center for Intelligent Infrastructure, is researching concrete sensor networks that save governments—and by extension taxpayers—significant money and hours.[15] Lu's research uses IoT sensors embedded in concrete that provide real-time information on various aspects of the material, like moisture levels, strength, pH levels, etc. These "plug and play" sensors are easy to use and together create a platform that provides the end users with a visualization of this information.

Thanks to this specific data, construction decision making can become incredibly precise. Traditionally, the construction industry is based on experience and educated guessing, but Lu is making the entire process more data-driven, which leads to significant cost savings. In pilot testing, there was a 35 percent increase in construction productivity, a 25 percent reduction in insurance costs, and a 15 percent reduction in material costs. Additionally, using data to determine how long to spend on construction and when repairs should be made saves 4 million hours a year and 3 billion gallons of gas from construction traffic, according to Lu.

B. Girder Sensors

Digital platforms and AI dramatically improve preventative maintenance. Sensors embedded in bridges and buildings forewarn of problems not seen by the human eye and in advance of a scheduled inspection.

In South Carolina, girder sensors were installed on several bridges to measure carrying capacity 24/7. The South Carolina Department of Transportation (SCDOT) found that human inspectors tended to underestimate bridge strength, which led to unnecessary replacement and maintenance costs. The real-time information from the sensor monitors provided SCDOT with an up-to-date view to keep bridges safely in service an extra few years before replacing them.[16] Additionally, SCDOT was able to save money thanks to the sensor data. The team solved one bridge's structural problems with a $100,000 retrofit, rather than spending $800,000 to replace it,[17] and the sensor platforms on eight bridges cost $400,000 in total and saved taxpayers $5 million.

C. Roving Sensor Platforms

In some cities, garbage trucks are not just for picking up waste; they serve as roving sensor platforms that alert the street department about potholes and road problems before they become major issues. Smart garbage trucks developed by researchers at the MIT Senseable City Lab for the city of Cambridge can send information back to city officials to analyze.[18] These sensor platforms drive predictive interventions and targeted repairs that extend the life cycle of the street assets and reduce costs in the long term.

D. Sewer System Sensors

At another level, digital platforms can help us rethink the very nature of the asset and potentially give new life to older infrastructure. Now-Secretary of Transportation Pete Buttigieg deployed smart sensors in South Bend's sewer system when he was mayor.[19] He wanted to innovate how the city handled sewer overflows; traditionally, the combined system handled both rainwater and raw sewage, and heavy rains would lead to overflow that would dump sewage into the nearby St. Joseph River. Under Secretary Buttigieg, the city's Public Works division deployed a sensor network inside the sewer system that turned pipes designed to convey sewage into short-term storage structures to avoid combined sewer overflows. The sensors are part of a box set that includes a microprocessor, radio, and battery; sensor boxes are attached to 150 manhole covers and broadcast data every five minutes, letting city workers know when and where to direct sewer water within the system to store the water in emptier pipes and avoid overflows. This single technology project saved hundreds of millions of dollars as well as avoided river pollution.[20]

2. Enhanced Infrastructure Safety and Resilience

There is nothing quite like an infrastructure disaster to get the American public's attention, whether it is the discovery of dangerous levels of lead in Flint, Michigan's drinking water system; the failure of the Texas electric grid; a cracked and almost-severed steel beam on the Hernando de Soto Bridge closing the Mississippi to barge traffic; or a near-catastrophic dam failure in Oroville, California. These crises disrupt businesses and lives, cost billions of dollars, and result in numerous deaths.

Infrastructure tragedies, which have become far too commonplace, serve as a stark reminder of infrastructure's critical role in our lives. Modern society is dependent on a vast array of bridges, roads, ports, airports, water systems, transit systems, and the like, and the public expects this infrastructure to be safe, reliable, and able to perform at reasonable levels. When they do not, the public is understandably outraged.

The importance of safe infrastructure simply cannot be overstated. Intelligent infrastructure offers an innovative and more efficient approach to enhancing the safety, reliability, and resilience of our nation's critical infrastructure. From highways to sewers, our health depends on safe infrastructure.

A. *Bridges*

Bridges serve as an excellent example of the practical application of smart sensors and intelligent infrastructure in enhancing safety. Smart bridge technologies are being implemented in the redesign and repair of existing bridges, providing more efficient monitoring and inspection in real time.

There are more than 617,000 bridges across the United States, with nearly 231,000 of those in need of major repair work or replacement, according to the American Road & Transportation Builders Association (ARTBA).[21] That is 37 percent—more than one-third—of all U.S. bridges. American drivers cross these failing bridges 1.5 billion times per day, representing one-third of all daily bridge crossings.[22]

More than 46,000 of those bridges (or 7.5 percent of the national inventory of bridges) are considered "structurally deficient" and in poor condition—and these are crossed more than 170 million times a day.[23] Notable structurally deficient bridges include New York City's Brooklyn Bridge; Washington, D.C.'s Theodore Roosevelt Bridge; the San Mateo-Hayward Bridge crossing San Francisco Bay; Florida's Pensacola Bay Bridge; and the Vicksburg Bridge in Mississippi.[24]

According to the American Society of Civil Engineers (ASCE), at the current rate of investment in bridges, it will take until 2071 to make all of the repairs that are currently necessary, and the additional deterioration over the next 50 years will become overwhelming. The nation needs a systematic program for bridge preservation, whereby existing deterioration is prioritized and the focus is on preventive maintenance.

Most bridges still require field methods to assess damage, including visual inspection, dye penetrant testing, magnetic particle testing, and ultrasonic techniques. Yet these field methods can miss structural problems or fail to catch them in time to prevent a catastrophe. For example, in the case of the Minneapolis I-35W Mississippi River bridge, which collapsed on August 1, 2007, resulting in the loss of 13 lives, the National Transportation Safety Board (NTSB) ruled that 16 of the gusset plates that connected the steel trusses failed.[25]

This tragedy might have been prevented had the bridge been equipped with a network of smart bridge sensors providing continuous monitoring of various properties. For instance, the six-lane, two-mile Charilaos Trikoupis Bridge (Rion-Antirion Bridge) in Greece has 100 sensors (300 channels) that monitor its condition. The bridge opened for use in 2004, but the sensors soon detected abnormal vibrations in the cable. Thanks to the quick detection, engineers were able to install additional weight to dampen the cables.[26]

The St. Anthony Falls Bridge, which replaced the Minneapolis bridge that collapsed, was completed in September 2008. It has not only carried traffic over the Mississippi River in Minneapolis but is also funneling sensor data to researchers and Minnesota Department of Transportation (MnDOT) bridge engineers. With over 500 sensors, the bridge can monitor strain, load distribution, temperature, bridge movement, and other forces.[27] The total cost for the sensing system was about $1 million,[28] a small fraction of the bridge's $234 million price tag.

Sensors help designers and bridge managers learn more about how bridges move and flex over time, enhancing safety with real-time data. There are natural shifts in the concrete and bearings of bridges, but these systems continuously gather data about minute changes, catching unnatural and potentially dangerous changes accurately and quickly.

B. Disaster Preparedness and Response

Smart sensors are being used for inundation forecasting to enhance emergency preparedness for flooding from storm surge, rain, and tides. The Hampton Roads area of Virginia, comprising Virginia Beach–Norfolk–Newport News, installed StormSense, a low-cost, low-energy system of smart water sensors, to enhance the capability of their communities to prepare and respond to the disastrous impacts of sea-level rise and coastal flooding.[29]

Built in collaboration with Virginia Institute of Marine Science (VIMS) and its Tidewatch Network, StormSense "advances the field of emergency preparedness for flooding resulting from storm surge, rain, and tides, via a network of 'Internet of Things' (IoT)-enabled water-level sensors."[30] Predictive capabilities around flooding, coupled with real-time information, are critically important to protecting residents of the area.

Prior to the introduction of StormSense, Hampton Roads, VA, had a total of six publicly available water-level sensors within its 527 mi² land area. Federal entities installed and maintained these six sensors to assess inundation timing and depths. As a result of deploying smart water sensors throughout Hampton Roads and Virginia Beach, the total number of publicly accessible water-level sensors in the region went from six to 40, which was a five-fold increase from 2016 to 2017. The system also inputs data from 25 out-of-network sensors from the National Oceanic and Atmospheric Administration and United States Geological Survey in order to guarantee a more comprehensive view of real-time flood conditions.[31] Also, the IoT sensor approach is cost-effective and replicable, as StormSense's IoT sensors are indicated to be 98 percent as accurate as the federal sensors, at one-tenth of the cost.

C. Public Health

Another way that sensor platforms can make communities safer is through networks focused on public health. Digital water monitoring can be used at many different levels, from incoming pipes to outgoing waste, to understand community health and to identify and remove toxins.

Traditionally, water management tested drinking water at supply intake points or at treatment plants. However, the aging water infrastructure in this country contains significant amounts of contaminants,[32] like lead or other heavy metals, which leach into drinking water during transportation to homes and businesses and are therefore not detected by single-point tests. To address this, sensors that detect contaminants can be placed throughout pipelines,[33] sending data back to a main digital platform that monitors and reports on levels of lead, bacteria, and other toxic substances.

In 2018, Memphis, Tennessee was struggling with high pH levels and toxic pollutants in the city water, an issue that would regularly arise and require extensive monitoring and treatment. That year, the Memphis Division of Public Works decided to pilot a sensor network that could monitor things like pH levels, suspended solids, and nutrient compounds;[34] the individual sensor would then transmit data through cellular networks to a server platform that would visualize the information in almost real time. This smart digital platform was highly successful, and the city deployed more sensors once the pilot was complete.

For its part, the government of Ann Arbor, Michigan uses real-time smart water technology to monitor water conditions. The city deployed Open Storm,[35] a package of open-source sensors, hardware, and algorithms, to measure and control stormwater. Sensor nodes collect data on water flow and quality, then transmit it via a cellular network, providing a real-time, instant snapshot of water conditions.

As part of the project, valves have been installed on city water systems to open and close after a storm through remote control, releasing or holding water.

Likewise, many cities are monitoring wastewater products to better understand community health by detecting things like viruses and drugs. Although detecting viruses in wastewater is not a new technology, it has become increasingly important as the world faces the COVID-19 virus. Many people infected by COVID are either asymptomatic or infected (and contagious) before they show symptoms. By monitoring sewage, cities have been able to identify outbreaks before individuals even knew they were sick,[36] helping to guide public health policies, including lockdown measures, and contain outbreaks. Wastewater sensor networks can also scan for drugs like cocaine or opioids,[37] which can help identify community drug exposure,[38] facilitate partnerships with pharmacies, and guide intervention efforts.

D. Dams and Levees

The average age of the 91,000 dams in the United States is 57 years old, with roughly 15,500 qualified as high-hazard dams, which means that "failure or mis-operation is expected to result in loss of life and may also cause significant economic losses."[39] Meanwhile, with an estimated 100,000 miles of levee nationwide providing flood protection for an estimated 43 percent of the U.S. population, the nation's levees are, on average, 50 years old, and many were built using less rigorous engineering standards than are currently acceptable. Despite facing increased stress from climate change and other factors, both our nation's dams and levees register a "D" rating from the ASCE, among the lowest ratings of all infrastructure contemplated within the ASCE quadrennial report card.

The catastrophic consequence of this deteriorating infrastructure is the stuff of headlines, from the 2005 levee breaches during Hurricane Katrina to the 2017 Oroville Spillway disaster in California and the 2020 Edenville Dam collapse in Michigan. While there is no clear consensus on the exact number of dam and levee failures in the U.S. over the past decade, there is near-universal agreement that the nation's dams and levees are in urgent need of capital improvement and repair.[40] As America moves to upgrade and modernize its national inventory of dams and levees, however, it must resist the urge to simply swap decaying structures with like-in-kind replacements. It should instead seek to embrace smart dams and smart levees in an effort to ensure that the public is better protected through real-time information and predictive analytics going forward.

For instance, DamWatch is a national system to detect incidents that could imperil nearly 12,000 dams across the country. Using multiple data streams (including national seismic and meteorologic data), DamWatch issues alerts whenever events like heavy storms or earthquakes threaten a dam in the system.[41] It incorporates all the dams in 47 states that are "federally assisted" by the U. S. Department of Agriculture's Natural Resources Conservation Service (NRCS). With this data, the NRCS helps local entities, conservation districts, and municipalities with the planning and construction of water-control projects and advises them on continuing management and maintenance.[42] The system not only distributes alerts to key parties but also provides secure, web-based access to extensive design and maintenance data about the threatened facility.

Likewise, dams in Europe are now being built with systems combining sensors, embedded in urban flood embankments, with predictive breach and flood consequence models.[43] This new approach to dam and levee monitoring uses cloud computing, sensor technology, and predictive models. It contains a cascade of physical process models for levee and dam reliability, breaching, flood spreading, and life safety, which enables officials to run scenarios of levee or dam failure based on real-time information and assess the resulting flood consequence for emergency management. It also allows for predictive analytics, coupled with real-time information, to help prioritize maintenance activities and prevent potential failures.

Smart dams and levees provide intelligence to end users about past, current, and expected conditions, allowing them to make informed decisions about maintaining appropriate flood protection levels. The "intelligence" of this infrastructure is not only found in the application of sensor technology but in using those sensors to avoid failures and drive maintenance activities.

At present, dam and levee safety is primarily assessed through regular visual inspections carried out by engineers. Given the vast numbers of dams and levees in the United States, these inspections occur every few years at best. As a result, it is impossible to collect the information needed to ensure continued functionality and safety. The data that the IoT sensors collect can facilitate new and improved public policy, which in turn helps to improve infrastructure reliability and safety as operators are armed with better information on maintenance and necessary work.

E. Transit and Transportation

In Arizona, localized monsoons quickly sweep dust across highways, severely limiting visibility and creating unsafe road conditions. In the past 15 years, these monsoons have led to several deadly accidents along a stretch of interstate I-40 between Tucson and Phoenix. Seven years ago, the state's Department of Transportation (DOT) developed a dust detection sensor that could determine visibility by measuring the concentration of dust particles in the air.

A few years after developing these sensors, the DOT started a Transportation Systems Management and Operations (TSMO) division to begin work on an interconnected sensor platform that could be installed along 10 miles of the most dangerous stretch of highway. David Locher, now TSMO's systems maintenance manager and a former DOT engineer, helped build the dust detection system.

According to Locher, who now manages the team that maintains the system, the goal was to have a fully automated, self-contained system that would detect drops in visibility due to dust, and then slow driving speeds along that stretch of highway accordingly. There are 13 sensors that translate visibility into feet and feed that information back to the state's Traffic Operations Center (TOC). The Center is staffed 24 hours a day, seven days a week, but staff don't need to oversee the platform thanks to the AI system that recognizes specific visibility drops and triggers speed changes once alerted to the lowered visibility. The system "tells" the smart speed signs to reduce speed limits by ledges over a period of two minutes to bring traffic down to a safe speed.

In addition to these smart speed limit signs, there are messages at each end of the 10-mile stretch that warn drivers that this area has variable speeds and to expect speed limits to drop in accordance with visibility to keep them safe. There are also embedded loop sensors in that area of pavement to measure speeds, so TOC staff gather data and check if people are actually following the signs and lowering their speeds. Another use for the data is looking at trends around environmental predictive factors, part of the project that is shared with forecasters at the National Weather Service. This system has been named an Infrastructure Gamechanger by the ASCE.[44]

Overall, intelligent infrastructure and sensor networks enhance public safety by ensuring the integrity and safety of the infrastructure itself. Monitoring by platform is generally safer, allowing for broader and more objective conditions analyses. By embedding sensors that connect to an understandable digital platform, government officials have a better understanding of how, when, and where to make repairs, which can lead to significant cost savings and an increase in reliable, safe infrastructure.

3. Sustainability

While smart sensors have been used for years in energy conservation and management, the application of digital technology and smart sensors is rapidly expanding into other areas of environmental sustainability.

A. *Smart Water Systems*

The water challenges facing the United States are as complex as they are diverse, ranging from water supply scarcity triggered by climate change and population growth to aging distribution systems and treatment facilities to alarming levels of forever chemicals, like arsenic and lead, in drinking water. In response to such challenges, officials are increasingly turning to intelligent infrastructure.

With the U.S. Bureau of Reclamation likely to issue a Level 1 Water Shortage Declaration for the first time in its history,[45] and the American West facing an unprecedented drought, the need to protect our nation's valuable water resources has never been clearer. In many areas of the United States, the "frequency, intensity, and duration of drought events is increasing."[46] This pattern is expected to continue and shift outside of historical trends, making it even more important to protect our nation's water supply.

Despite water scarcity, aging infrastructure, such as leaky pipes and water mains, is estimated to result in the loss of 2.1 trillion gallons of treated drinking water in the U.S. each year,[47] representing approximately 14 to 18 percent (or one-sixth) of the nation's treated water.

To mitigate water stress, water resources need to be managed more effectively. The use of smart technologies can improve water resource management, which can help to abate water scarcity. For example, smart water grids are being used to improve the management and preservation of water resources, integrating technology into water infrastructure and management systems to provide a more efficient water supply network.

A smart water grid leverages IoT devices (such as sensors, meters, and controllers), in conjunction with data analytics, to monitor, manage, automate, and control the distribution of water. It ensures that water is distributed efficiently to citizens while also safeguarding water quality standards. Importantly, it also minimizes inefficiencies in the current water distribution system. The smart sensors enable the collection of extensive data regarding water pressure, availability, contamination, and defects in the water distribution system. The data is collected and analyzed in real time, minimizing water losses and increasing the efficiency of the system.

Maintenance of a smart water grid is also relatively easier when compared to conventional water distribution systems. Since the sensors collect data in real time, they can detect shortcomings, such as low water pressure, clogging, or leaks, as soon as they occur. Then, measures can be taken to resolve the issues quickly. Furthermore, an automated water distribution system can even stop the water supply autonomously as soon as it detects any mishaps, such as a burst pipeline or contamination in the water quality, alerting authorities in a matter of seconds. The authorities can then carry out the required maintenance procedure, thus ensuring the water grid runs efficiently, with minimal interruptions.

Smart water systems, sensors, and technologies are being implemented all over the world. For instance, the State of California has employed low-cost solar-powered, satellite-connected sensors to pilot technologies, which can accurately monitor and track groundwater use in one of the largest and most at-risk aquifers in North America,[48] northern California's Sacramento-San Joaquin River Delta. The sensors will transmit water extraction data to orbiting satellites, and then to the IBM Blockchain Platform, facilitating the exchange of water rights in real time.

Stakeholders, like farmers, regulators, consumers, and investors, have access to an online dashboard that monitors and tracks groundwater usage to demonstrate how sustainable pumping levels can be achieved through the trading of groundwater use shares in California. Individual users who require groundwater amounts beyond their share can purchase groundwater shares at a market-regulated rate from users who do not require their full supply.[49] The future success of these sustainability plans hinges on the ability to track and report groundwater use as well as the possibility to trade groundwater shares.

On the other coast, DC Water, the independent authority, supplies 99 million gallons per day of fresh water for residents, workers, and visitors in Washington, D.C. (and its surrounding environs) and manages some 1,300 miles of pipes and 1,800 miles of combined sanitary sewers. As some of this infrastructure is over 100 years old, it can be both costly and difficult to maintain. To automate the detection and classification of pipe anomalies, DC Water has employed Microsoft's Cognitive Toolkit, which uses sensors, AI, and the IoT to conduct predictive analytics on the water distribution system, including proactively identifying potential water main break scenarios and water quality challenges. This system has reduced the inspection and detection process from hours to minutes, allowing DC Water to optimize services at a lower cost while ensuring the safety and reliability of the system.

DC Water is also employing artificial intelligence under the umbrella of Pipe Sleuth, an innovative process that allows for the detection of pipe defects[50] in the sewer system. That information is plugged into DC Water's investment models, helping to decide where to prioritize the repair and/or replacement of infrastructure, to better target pipe upgrades. Previously, such analysis was conducted via cameras manually lowered into sewers, with operators watching closed-circuit TV footage to code and classify findings, and engineers following up to identify pipe defects. Published reports suggest that Pipe Sleuth can process the video more efficiently, in approximately 10 percent of the time,[51] while also substantially reducing the cost (from $7 to $9 per linear foot to $2 to $3 per linear foot). It also leads to a higher-quality inspection since the tool can detect more subtle defects and does not suffer from the human operator fatigue factor.

However, water conservation is not limited to utilities. Intelligent infrastructure and smart sensors are also being used to assist in demand-side conservation efforts. After being impacted by drought, Fountain Valley, California deployed smart technology, including smart meters, to show municipal officials where and how water was being used in the municipality. It also gave the community information about water consumption and identified areas for improvement. As a result, Fountain Valley reduced water usage by 23 percent.[52]

B. Construction Processes

Sustainability is an overarching goal for cities, and smart sensors can support these goals in multiple roles and functions, like decreasing emissions, conserving energy, and eliminating material waste.

In addition to the cost-savings outlined earlier, Professor Lu's intelligent infrastructure concrete research at Purdue has important sustainability implications. Since the sensor platform identifies micro-cracks and poor pH levels that can cause corrosion, it's able to detect necessary repairs faster than a human inspector. Machine learning can be trained on the data and visualizations from the sensors to alert stakeholders when and where repairs are needed.

This is a safer and more sustainable system, as issues that are detected early require less labor and fewer materials to fix. As machine learning processes information from the sensor platform, it can not only give accurate recommendations on repairs but also learn to more accurately predict where and what type of issues will appear, which Lu describes as a "paradigm-shift" for the entire industry. In turn, this information can be used by researchers and manufacturers to develop better, stronger materials and even types of concrete that absorb carbon,[53] produce fewer greenhouse gasses, and self-heal. According to Lu, "Preventative maintenance makes smart infrastructure more sustainable." This is particularly important in the United States, as most of the national infrastructure has a C- grading and will need to be repaired sooner than later.[54] Making these necessary repairs and upgrades using sustainable materials will be incredibly important for the longevity and sustainability of the country's infrastructure.

There are many other ways that sensor platforms can contribute to sustainability. One way that smart infrastructure can be green is through self-charging sensors; rather than pull energy, a new type of wireless sensor "uses only self-generated electrical energy harvested by piezoelectric transducers directly from a structure under vibration,"[55] like a bridge or road. Additionally, low-cost sensors make this technology more accessible,[56] and therefore a more sustainable and long-term option. Sensors also help guide sustainable infrastructure investments by monitoring energy system efficiency, optimizing energy consumption in buildings based on occupancy, and analyzing and alerting stakeholders to pollution levels in the air or water.[57] When considering what type of sensor network to deploy, public officials should keep in mind the longevity, sustainability, and maintenance costs.

C. Curb, Sidewalk, and Mobility Management

IoT platforms facilitate extraordinary improvements in many areas related to transportation and mobility. In 2018, parking expert Donald Shoup estimated that, on average, 30 percent of the cars in congested downtown traffic were cruising for parking.[58] This was due to poorly timed traffic signals producing excess queuing, which generates carbon and wastes time.

In 2020, the highly respected Southern California Association of Governments (SCAG) undertook a study in Los Angeles to understand last-mile delivery issues as well as the waste, pollution, and frustration unleashed by delivery services competing for curb space.[59] The study underscores the complexity of the system while making various recommendations on the allocation of curb space, like zone pricing determined by sensors, consolidated shipment software to manage deliveries, and "smart lockers" as mini distribution centers.

There are multiple stakeholders in this work, and companies like the United Parcel Service (UPS) have been partnering with city officials in Europe and North America to coordinate more sustainable delivery methods, such as electric vehicle fleets and smart-grid simultaneous recharging technology.[60] Researchers in Latin America are exploring the idea of Urban Logistics as a Service,[61] which would integrate logistics services and assets into a digital platform that could be accessed by all relevant stakeholders, like traffic and transportation officials, local policymakers, and delivery companies. With a technological data-sharing platform that is accessible across sectors, urban logistics could be studied and then streamlined to reduce congestion and pollution.

Digital platforms also enhance critical operation and planning capacity. Platforms can bring together the data that city officials need to manage conflicting and shifting uses for streets, curbs, and sidewalks. In some cities, drivers can use their phones or in-dashboard devices to pay for parking, which also generates information for the city, like where drivers use metered infrastructure versus phone apps to pay for parking. Transportation officials can regulate scooters and transnational corporations (TNCs), such as Uber, which also produces data. Eventually, autonomous vehicles will compete for curb usage as well, and today's outdoor cafes crowd into these same spaces. A digital platform will help the city understand and referee use, ensure equity is addressed, provide dynamic pricing in order to better adjust behaviors, and enhance revenues.

All of these complex problems could be solved with new infrastructure that includes a digital and geospatial platform to manage the interconnected and competing uses of vehicles such as bikes, pedestrians, scooters, TNCs, trucks, and personal cars.

4. Equity, Social Justice, and Community Involvement

Intelligent infrastructure presents an opportunity to combine physical and digital infrastructure and harness technological innovation to reduce inequalities and improve inclusion. As America looks to rebuild its civil infrastructure, intelligent infrastructure can be used to help remedy past wrongs, reconstruct a more just urban environment, and improve the health and economic well-being of those who have been systemically disadvantaged by our past and current investments and programs. The geospatial digital layer allows both officials and residents to see the interconnectivity of various assets in a specific location. With the right digital layer, officials can overlay and manage different factors by location, such as how traffic patterns lead to worse air quality in underserved communities.

A. *Air Quality*

Poor air quality is the largest environmental health risk in the United States, and fine particulate matter (PM2.5) pollution is especially harmful. More than 100,000 people die each year from diseases caused by PM2.5,[62] such as heart attacks, strokes, and lung cancer. However, not everyone is equally exposed to poor air quality.

Black and Hispanic communities bear a disproportionate burden from air pollution. First, Black Americans are, on average, exposed to about 56 percent more PM2.5 pollution than is caused by their consumption; for Hispanic Americans, that number is slightly higher at 63 percent.[63] Yet despite causing less air pollution, both groups are disproportionately more likely to have high rates of asthma, cardiovascular disease, and premature death.[64]

As awareness and concern about PM2.5 spreads, cities have turned to the Internet of Things (IoT) to measure air pollution. With this data, city officials can map areas of high pollution, identify polluters, and analyze potential interventions, in addition to tracking changes over time and measuring progress. There are three main categories of initiatives: those that integrate air pollution sensors into existing infrastructure, those that utilize mobile sensors, and those that analyze cell phone data to dynamically understand where residents are exposed to poor air quality.[65]

Air quality sensors integrated into existing infrastructure track air quality in key areas. In 2014, the Chicago Department of Innovation and Technology deployed its Array of Things, a citywide network of sensors mounted on lampposts,[66] developed with the Argonne National Library. Using a technology called "waggle chips," these sensors track the presence of a number of air pollutants, including carbon monoxide, nitrogen dioxide, ozone, and particulate matter,[67] with plans to monitor volatile organic compounds in the near future. Chicago can use this data to take preventative action, predict poor air quality, and share data with the public via the city's open data portal.[68]

A distinct advantage of infrastructure-embedded air sensors is their longevity; integrating sensors into lasting features of the urban landscape allows for data collection over time, mapping trends without additional interventions. Moreover, these systems can provide instantaneous air quality data, which may be used to both enforce regulations and influence the actions of citizens during times of poor air quality.

B. *Adaptive Infrastructure*

New investments, to the extent possible, need to incorporate tools that help users and officials adapt that infrastructure to changing conditions and future uses. These changes may be driven by environmental conditions, land use, or resident behavior.

The forces of climate change, rising sea levels, and widespread pollution are increasingly threatening marginalized communities across the globe. In the United States, this issue is compounded by an aging and underfunded infrastructure system that leaves many regions dangerously vulnerable to extreme weather, natural disasters, and unsafe housing and transportation.

Infrastructure resiliency is especially important in acute disaster planning. Unlike longer-term, slower degradation from pollution or aging sidewalks, natural disasters are an immediate emergency that local governments must prepare for, with a particular focus on equity. Research has proven that socially vulnerable groups, like those with disabilities, the elderly, and racial and ethnic minorities "are less likely to recover and more likely to die" in a disaster.[69] Smart infrastructure is an issue of life and death in these situations, and future planning—especially in light of more extreme weather events—is crucial for equity.

Recent heatwaves across the country overpowered cities and, according to the Centers for Disease Control and Prevention, led to an increase in deaths from not just heatstroke but cardiovascular and respiratory diseases that are exacerbated by extreme heat. Urban heat islands are more likely to be concentrated in communities of color,[70] meaning that the adverse health effects and risk of death are inequitably spread across cities. In Richmond, Virginia, researchers utilized stationary sensors to gather and analyze air quality and temperature data throughout the city. Focusing on the 10 hottest days of 2019, they found that both the temperature and air pollution were worse in the East End,[71] a historically Black neighborhood with the majority of the city's public housing.[72] Thanks to the sensor platform, the city can now address the real racial discrepancies that are coming from the built environment and utilize smart infrastructure as an alert system during heatwaves.

Infrastructure resilience will be a serious boost for minority and low-income communities that are often the most impacted by climate disaster and live on the frontlines of rising sea levels, degrading environments, and worsening storms. Real-time, anonymized data can be used to prioritize budget expenditures and other interventions to protect at-risk communities.

For decades, public transit was built on the model of an able-bodied male commuter; however, data proves that there are clear gender differences in how riders utilize transportation,[73] and that people with disabilities have significantly more difficulty in getting the transportation they need.[74] In addition, as poverty grows in close-in suburbs and jobs move to other suburbs, we see transit systems that often poorly serve those who need them most: the struggling, minority workers. A more adaptable multi-modal approach requires a digital infrastructure that allows officials to make frequent changes. Also, aging public transit infrastructure simply compounds the problems that already exist—broken elevators, if there are elevators at all, limit those who use wheeled mobility devices or anyone with a stroller. Sidewalks in poor conditions, if there are sidewalks at all, limit the ability for these same populations, as well as the elderly, to access transit points like bus stops.

Cities around the world are modeling innovative, resilient transit infrastructure to address these discrepancies. In Vancouver, Canada, long-range radio frequency identification (RFID) sensors are installed at the accessible gates at train and bus stations; riders with limited mobility have special transit cards with an RFID chip that are read by the gates,[75] which swing open without requiring the ability to tap a transit pass. Additionally, many cities are installing smart streetlights in public areas, like pathways and train stations, to provide safe and well-lit areas for women to travel. In the United Kingdom, researchers studying infrastructure revitalization, gender, and safety found that the number one tech solution cited by women in the study was better street lighting;[76] they also mentioned the concerns over poor pavement conditions, all things that can be addressed by intelligent infrastructure. Resilient, smart infrastructure aids and improves human resiliency.

C. Funding Decisions and Community Participation

Although equity is, or should be, a part of each discussion, the safety, funding, and reliability of infrastructure has long been inequitable. Many cities are now using data, GIS, and sensor platforms to guide where to prioritize investments, often revealing that decades of systemic bias have led to crumbling infrastructure in low-income areas and communities of color.

For example, the Oakland Department of Transportation (OakDOT) has worked closely with the city's Department of Race and Equity to identify and map inequities and then conduct new infrastructure projects fairly and equitably.[77] Traditionally, paving projects and street repairs were focused on major streets, with a few local streets chosen for improvement, mainly based on complaints to the city council. However, a major 2019 multi-year infrastructure bond of $100 million held 75 percent of the budget for local streets.[78] Before distributing the funds, OakDOT used mapping, data collection, community engagement, and research to show that neighborhoods of color had longer commute times, worse road conditions, and fewer protected bike lanes.[79]

Thanks to this data analysis, OakDOT utilized a percentage formula to "distribute funding for local streets by the share of underserved populations and share of local street miles in poor condition,"[80] which prioritized areas that had been neglected and are majority non-white. Despite the COVID-19 pandemic, The Great Pave is on track to be completed on time and increase equity with fair funding.

The collection and analysis of anonymized, real-time data can and should be used to help make budget decisions and prioritize funding for both capital investments and ongoing preventative maintenance. For example, South Bend, Indiana used digital twins (computer-based replicas of physical assets and cities)[81] and neighborhood digital responses to help with design planning for a major citywide parks' investment. Responses increased localized spatial input about the average park user's age and whether park visitors thought equity and design were being adequately addressed.[82]

IV. Challenges

While intelligent infrastructure holds great promise toward improving life-cycle asset management, enhancing safety and resilience, fostering conservation and sustainability, and promoting greater equity and social justice, its broadscale application to civil infrastructure also represents something of a challenge.

1. Cost

Even though the use of intelligent infrastructure can significantly reduce life-cycle asset costs, it is often difficult to convince public agencies to invest in these systems given persistent fiscal restraints. While the integration of smart sensors into civil works will admittedly cost more than using traditional processes, these additional costs are more than compensated on a life-cycle basis due to better-informed decision making around maintenance. Focusing only on first costs is as dangerous as it is short-sighted, particularly when a marginally greater investment will result in higher safety and resilience standards as well as lower life-cycle costs.

That said, intelligent infrastructure is generally not cost-prohibitive. Case in point: the total cost of a 500-sensor monitoring system for the St. Anthony Falls Bridge replacement was approximately $1 million, less than 0.5 percent of the total construction cost. These sensors are not only reducing operations and maintenance costs by providing real-time information on bridge performance but are also helping to ensure that the bridge is safe and reliable for the traveling public.

2. Technology

The second challenge is the technology itself, which is still evolving. Currently, there are limited power resources for operating these smart sensors and sensor networks. When wireless sensor networks (WSNs) were first introduced, the energy required to power them was a valid concern due to battery limitations. Energy harvesting technologies were then developed to extend the lifetime of WSNs by addressing the energy constraint problem. Recently, a new generation of WSNs based on self-powered sensors are bridging the gap between the harvested energy and the energy required for sensing, computation, storage, and communication. These self-powered sensors are increasingly being used in civil infrastructure. That said, there is still room for improvement, which has resulted in some public agencies deferring deployment of these systems. As the pursuit of perfection is the enemy of good, public authorities should not defer investment into WSNs; the technology available right now is sufficiently advanced to perform reliably across multiple infrastructure assets.

3. Cybersecurity

While smart infrastructure offers many opportunities, it can also expose our civil infrastructure to potential cyberattacks. Public agencies must be especially cognizant of cybersecurity issues when deploying and operating intelligent infrastructure, as these systems and networks will often require additional protection against cyberthreats. Nonetheless, most intelligent infrastructure systems are now being designed and deployed in ways that maximize cybersecurity. Recognizing the vulnerability of intelligent infrastructure, proprietors have pioneered the adoption of security best practices, including a zero-trust model, accelerated movement toward secure cloud services, and consistently employing foundational security tools, like multi-factor authentication and encryption.

V. Conclusion and Policy Recommendations

Intelligent or smart infrastructure integrates digital technology and smart sensors to provide self-monitoring and improve decision making. This drives efficiency and cost savings, reliability, security, safety and resilience, user interaction and empowerment, sustainability, and service quality.

Intelligent infrastructure offers 24/7 access to analytics and reporting, monitoring an infrastructure asset's performance data in detail, remotely and in real time. It processes millions of data points per day from multiple sensors and sensor types. This gives engineers and public officials the ability to detect and deal with problems before they become critical, which helps lower costs and improve safety while better managing future planning.

Despite its promise, however, it has been largely ignored within the context of discussions around an infrastructure plan. The United States must invest in rebuilding its aging infrastructure, but this should not mean that we reinvest in Jurassic-era technologies and structures. According to Director Cleckley, "Digital infrastructure is the future and, quite frankly, if the cities don't do it now, they're going to be behind decades, because the industry is not stopping."

The nation must seek to upgrade and modernize its infrastructure, preparing it for a future in which our physical and digital worlds are fully intertwined. To this end, any infrastructure plan should prioritize investments in intelligent infrastructure. Policy recommendations include the following:

1. Federal Level:

- Mandate or incentivize the incorporation of intelligent infrastructure sensors and networks into all projects receiving federal grants or loans. This could be done simply by including intelligent infrastructure as a project evaluation criterion for federal grants and loans (e.g., FTA, AIP, WIFIA/TIFIA, FRA, PID, RRIF, INFRA, etc.).
- Provide federal grants for R&D to advance the performance of self-powered sensors and fortify cybersecurity around both federally and locally owned intelligent infrastructure.
- Authorize and fund the United States Army Corps of Engineers, in coordination with the Bureau of Reclamation, to oversee the implementation of the DamWatch program for nationally owned and operated dams and evaluate the cost implications of its application to the National Inventory of Dams.
- Authorize and fund a Special Experimental Program to evaluate the challenges and benefits of intelligent infrastructure across multiple sectors (e.g., airports, water systems, flood risk management, roads, pollution abatement, etc.).
- Provide direct grant funding for incorporation of smart sensors into existing assets to communities that commit to utilizing data-driven budget decisions to foster social justice.
- Provide guidance and funding to local authorities for enhanced cybersecurity that includes hardening of digital infrastructure, including protection against ransomware and malware attacks.

2. **State and Local Level:**
   - Commit to life-cycle asset cost evaluation when making budget decisions around new infrastructure.
     - Better, more long-lasting projects are built when a project is scoped with digital infrastructure included from the start.
     - Aligning funding sources at the beginning of a new infrastructure project ensures that there is coverage for intelligent sensors, etc.
   - Invest the time and resources in a comprehensive asset management system. This system should include an inventory of all infrastructure assets that are owned or under control of the state or local entity.
     - At a minimum, the asset management system should include age, current condition, life expectancy, and a qualitative rating of community importance, data from sensors, and a system to continuously collect applicable information.
     - Public and open records laws should require that sensor information on infrastructure conditions be layered on GIS maps visualized for the public. The public needs more visibility into the state of its assets. The Governmental Accounting Standards Board requires reporting of certain information concerning infrastructure, but those reports often do not reflect the true condition of the asset and are used more by bondholders than the public.[83]
     - Sensors now located in trash trucks can measure pavement smoothness; connected devices at intersections can record dangerous conditions; vibration problems emanating from a bridge or wastewater pump can alert officials and local residents to issues.
   - The state is in an optimal location between local and federal leaders to change policy and make funding decisions for smart infrastructure projects.
     - Especially in regard to transportation, the state should lead funding allocations with digital infrastructure in mind, both by directing funding to projects that include smart city/IoT aspects and by requesting that as a part of transportation proposals.
     - The state is also in a position to create incentives for local governments by removing their match requirements. They can also encourage public-private partnerships to incentivize these intelligent infrastructure projects.
     - Local leaders have less flexibility and control over transportation projects that cut across multiple cities and counties. Therefore, states should be leaders in the identification and integration of systems and technologies that facilitate easy data sharing and understanding across different cities, towns, and counties.

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