A Policymaker's Guide to Digital Infrastructure

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Successfully building out both purely digital and "hybrid" infrastructure will unlock new economic opportunities, create jobs, and improve people's quality of life.

Infrastructure has always been important to nations' economic growth and success, but the infrastructure needed for today's economy is rapidly changing with advances in information and communications technology (ICT). This new infrastructure—some of it hybrid infrastructure that integrates both physical and digital aspects, some of it pure digital infrastructure—is critical to delivering the next wave of innovation and economic growth to all but the very poorest of nations.

Some have argued that there is little innovation in infrastructure because—just like 50 or even 100 years ago—cars still drive on roads; planes fly in the air; and trains run on tracks. And while there may be innovations in physical infrastructures (e.g., self-healing concrete), many of today's opportunities for improvement depend on embedding digital technologies in physical infrastructures.

Successfully building out digital infrastructure (hybrid and purely digital) across all types of infrastructure will unlock new economic opportunities, job creation, and better quality of life. Nations stand to benefit from digital infrastructure in the following areas:

- Capacity expansion: increased use of both existing and new infrastructures;
- Time savings and convenience: reduce congestion, simplify operations, and enable more informed decisionmaking;
- Cost savings: minimize waste, boost efficiency, and create more flexibility in the provision of key services;
- Improved reliability: reduce unpredictability and interruptions in the provision of key services; and
- Enhanced safety: improve resiliency to threats and interruptions.

However, there are numerous barriers to realizing the economic and societal benefits of digital infrastructure. These include costly and outdated regulatory policies, a lack of public funding for investment, a scarce talent pool of individuals trained in ICT skills, and largely ill-founded fears about the privacy and security of data.

Given these barriers, governments and the private sector should work together to develop comprehensive national strategies to facilitate more rapid development and deployment of digital infrastructures. In part this will also mean increasing public investment in digital infrastructure and reforming regulatory policies to create a friendlier environment for digital infrastructure. Finally, policymakers will need to prevent overwrought privacy concerns from slowing progress. These technologies can be deployed in ways that protect users' privacy, despite the often shrill warnings of privacy advocates to the contrary.

What is Digital Infrastructure?

Infrastructure can refer to a wide array of physical assets. One definition is "essential facilities, services, and organizational structures for cities and communities," and this includes not only roads and rails, but also fire stations, prisons, dams, roads, etc.[1] But this definition, while inclusive, is too broad not just for the purposes of this report but also for well-considered policy deliberations. For the purpose of this report, infrastructure refers to systems that societies use to transport goods, people, or information. This includes roads, pipes, wires, canals, and other parts of the built environment that facilitate transport. It does not include nodes, such as airports, oil terminals, and electric generating stations. Nor is cloud computing an infrastructure, as it refers to a broader system of nodes (server farms, software and communication protocols governing the movement and storage of bits, and the actual underlying communications layer, usually fiber optic cable). Infrastructure also does not encompass the items being transported, such as cars, trains, drones, and airplanes.

Digital refers to information technology systems that electronically collect, process, and transmit information. Therefore, digital infrastructures are those where at least a portion contains information technology. As such, there are two kinds of digital infrastructures, hybrid and dedicated. Hybrid infrastructures are traditional physical infrastructures that include added digital components. For example, traditional water mains would be infrastructure. But if the water mains are embedded with sensors to detect and transmit information on leaks, they become hybrid infrastructure. Dedicated digital infrastructure is that whose very nature is digital. Fiber optic cable to transfer digital Internet packets would be an example.

In some cases, infrastructures can gain intelligence by embedding digital capacities in the units traveling over the infrastructure. For example, digitally connected vehicles can bring intelligence to the surface transportation system even if the actual infrastructure does not include digital components.

Examples of and Opportunities for Digital Infrastructure

One way to categorize infrastructure is by what it transports. Table 1 classifies various types of infrastructure according to the links or pathways in the respective networks; the nodes where those links either terminate, come together, or cross; and the thing that is transported (whether goods, people, or information). This report examines digital infrastructure for each of these.

Table 1: Typology of Transportation Infrastructure

Infrastructure Type	Transport Link	Node	What is transported
Waterways	Canals, dredged waterways	Port	Ships
Waste	Sewage pipes	Sewage treatment facility, landfill	Sewage, garbage trucks
Rail	Railroads	Rail yards	Trains
Oil and gas	Pipelines	Refineries	Liquid fuels
Electricity	Wires	Generation plants and substations	Electrons
Water	Water pipes	Aqueducts, wells	Water
Roadways			Trucks, buses, cars
Bicycle systems	Roads, bikes, sidewalks	Houses/offices/stores	Bicycles/pedestrians
Aviation	Airspace	Airports	Airplanes
Mobile broadband	Spectrum	Cell towers/mobile phones	Bits
Fixed broadband	Wires, fiber-optic cables	Routers/servers	Bits
Satellite broadband	Spectrum	Satellites/routers	Bits

Movement of Goods

Economies depend on the movement of all kinds of different physical things: from inputs like oil and gas, electricity and water, to goods for production and consumption, to movement of waste products for processing and disposal.

Water

ICT can be used to better control, manage, and monitor water infrastructure, thereby reducing costs, improving efficiency, and increasing sustainability. Consumers and businesses can use smart meters to measure water usage; utilities can use smart pipes to monitor flow rates; water treatment facilities can use sensors to monitor water quality; and cities can use sensors to track rainfall and runoff. Better management of water infrastructure can help create a smarter water network that uses real-time data to detect and prevent problems such as leaks and theft, manage and monitor water quality and pollution, and better respond to flooding and droughts.[2] In addition, intelligent systems can be used to automatically optimize and manage complex water processing and treatment plants.

One important and growing way that ICT is being used to improve water management is with smart water meters. Until recently, most water meters were analog devices with no connectivity, which required a utility worker to view each meter on-site to determine use. Some utilities have begun to install digital meters that collect and transmit water usage data electronically, so that the company can remotely read the meter, saving the costs of manual reading. Some utilities have also begun to deploy smart digital water meters, which in addition to providing automatic meter reading, collect more detailed data and provide features such as remote disconnects.[3]

Smart meters can yield substantial savings and give consumers better control over their water usage. Smart meters can also help identify businesses or homeowners who ignore mandatory water restrictions more quickly. Over the long term, better data from smart meters can also help policymakers make the most of limited resources, such as by prioritizing the allocation of water efficiency grants to the most effective updates to businesses and homes, or by deploying pricing models that reward efficiency. Several California municipalities have turned to smart water meters in an effort to encourage efficient water use and punish bad actors during a drought. For example, the Long Beach Water Department installed smart water meters at a restaurant reported to have been wasting large amounts of water, which gave them the data to prove that the restaurant was in violation of water usage rules and issue a fine.[4]

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The United States is still in the early stage of deploying smart water meters. Nationwide, fewer than 20 percent of the 100 million metered-water customers have smart meters.[5]

Oil and Gas Pipelines

At the beginning of 2016, oil prices dropped as low as $27 per barrel from the 2008 peak crude oil price of $145.[6] As a result, the oil and gas industry has a newfound incentive to incorporate technology to reduce costs. There are three primary segments in the oil and gas industry: upstream companies (e.g., exploration, drilling, and extraction operations), midstream companies (e.g., transportation companies), and downstream companies (e.g., refiners and retailers).[7] Real-time information from hybrid infrastructure at oilfields and in pipelines must be readily accessible, so that different types of operations—upstream, midstream, and downstream—can collaborate, analyze, and make quick decisions about production and transportation.

Upstream oil and gas companies are placing connected sensors in their wells, from oil fields in hostile and remote locations to wells that were thought to have run dry. For example, some oil companies are placing sensors on equipment and high temperatures on the seabed to gather data about their deep-sea operations.[8] The data gathered from these sources can help oil and gas companies improve their performance, increase the efficiency of their rigs, reduce costs, and monitor the condition of drilling equipment from across the world. For example, engineers can apply analytics to data from wells to help map changes in reservoirs over time or to make production decisions.[9]

Midstream companies can use digitally connected pipelines to track varying types of fuels from source to refinery. Each year, pipeline leaks and stolen resources cost approximately $10 billion in losses in the United States alone.[10] To address this problem, midstream companies are installing sensors on pipelines or building new digitally enabled pipelines that detect leaks before they turn into disasters. Companies like Telus and Fox-Tek already offer Internet-of-Things pipeline-management services that rely on sensors at pump stations and fixed to the outside the pipeline.[11] TransCanada and Enbridge are testing multiple technologies that monitor different physical aspects of the fuel and the pipe—such as sensors that measure vapor, temperature, hydrocarbons, and acoustics.[12] Similarly, Rockwell Automation, a U.S. provider of industrial automation products, offers a series of smart sensors for oil pipelines that track equipment performance and health, monitoring fuel in real time and relaying that information to engineers who can address problems as they arise.[13] Companies are also using smart pigs—connected devices sent through the pipeline that monitor flow/blockages and structural health, which can also clean sedimentation buildup.[14]

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Electricity

The electric grid transports electrons from generating stations to end users, through a complex system of transformers, substations and wires. But for all its sophistication, most grids lack high levels of embedded intelligence. In contrast, the smart grid is a digitally enabled electrical grid that uses smart meters, advanced control systems, and communication networks to gather, distribute, and respond to information regarding the behavior of suppliers, consumers, and the grid itself.[15] A smart grid provides customers—residential, commercial, and industrial—with additional information, such as the amount of electricity used, when it was used, and how much it costs, to help them better manage their electricity use. The smart grid also automatically responds to failures and disturbances, sustaining operations even under adverse conditions.

Sensors and other devices linked by communication networks allow the grid to be monitored in real time and provide forensic analysis of power-grid disturbances. This allows the grid to be more resilient. For example, the smart grid can quickly reroute power in the event of failures. At the end user side, smart meters allow utilities to monitor consumers' real-time power usage and price electricity on a variable basis, charging less for power consumed at off-peak times.

The smart grid also enables renewable energy, including energy storage and plug-in electric vehicles. Energy-storage technologies, such as pumped hydro, compressed air, and chemical batteries, can play a major role in meeting peak demand requirements, and can be better used in the smart grid because of enhanced two-way communication networks. The smart grid will also deliver electricity more reliably to customers by monitoring, diagnosing, and responding to failures in power services. Reliable power is critical to traffic-management systems, security systems, hospitals, and the homes of seniors and other vulnerable populations. Preventing these failures saves billions of dollars.[16] Smart-grid technologies can also immediately detect and locate outages, allowing companies to alert police and other authorities, so that they respond more quickly to potential problems (such as traffic light failures).

Finally, the smart grid makes the electrical grid safer. The enhanced monitoring, mitigation methods, and control functions of the smart grid provide more reliable and safer power transmission and distribution. The smart grid offers enhanced cybersecurity through continuous monitoring to identify vulnerabilities and by providing the ability to remedy vulnerabilities prior to an attack.[17]

Freight Rail

Railways are increasingly integrating digital technology into their systems. These "smart-rail" initiatives can save lives, boost efficiency, cut costs, and provide convenience to consumers and businesses alike. Smart-rail systems use machine-to-machine (M2M) communication to turn train cars into interconnected communication hubs that transmit data to each other as well as a centralized network.[18] These systems are centrally managed through a cloud-based architecture and include GPS trackers on trains, wayside signals, surveillance cameras, wireless routers, and other tracking devices, enabling operators and control centers to track and control trains more efficiently.

The biggest advantage to smart-rail initiatives is increased safety. Currently, railway operators do not have full visibility into roughly half of the 140,000 miles of U.S. track.[19] The rail industry refers to this as "dark territory," and it is working diligently to close this gap through connected sensors. The industry has also been working to reduce human error through automation known as Positive Train Control (PTC). PTC monitors a train's location and speed, communicating a train's presence to operators. In May 2015, an Amtrak derailment in Pennsylvania resulted from the train going too fast around a bend, which could have been prevented had this technology been working (it had been installed on the tracks but was not operating).[20]

Operators are also equipping rail systems with detection systems to ensure that trains are "aware" of each other's positions and the trajectories of other trains.[21] This reduces the likelihood of collisions while allowing multiple trains to operate efficiently and safely within close proximity. If these systems are interconnected with signaling systems that run alongside train tracks, operators can command trains to stop based on the position of switches, track conditions, and conflicting movements at junctions and crossings.[22] Given the fact that trains often take miles to stop, highly accurate prediction and a high level of control can save lives.

Smart-train systems can also be used to improve the efficiency of operations and maintenance. By transmitting real-time data to a central system, smart-rail systems can help operators better allocate track capacity to avoid congestion.[23] Furthermore, a track's various sections can place strain on train wheels in different ways. For example, a sharp turn or steep section of track will wear on a wheel more than a flat or straight section. By monitoring the path of each train in real time as well as its braking patterns, an operator can use predictive analytics to optimize trains' maintenance schedules, minimizing the time a train is out of service for routine inspections and preventative maintenance, and also reducing costs in the process.

Finally, for commuter trains, these systems can provide data to inform passengers of departure, arrival, and train delays through mobile apps and other displays. This increases user convenience.

Ships and Waterways

By volume, 90 percent of the world trade is carried by sea.[24] The maritime industry, which consists of ships, harbors, and ports, is increasingly becoming connected to networks, enabling it to reduce human error, efficiently allocate ships, and track goods.

Shipping containers are increasingly managed by computer networks and algorithms. Currently, ships and ports use identification numbers and barcodes to track shipping containers by checking them in and out of each storage location, whether a port, a train, or containership.[25] But other than check-ins at distribution locations, many modern containers are not connected to any monitoring system that allows those awaiting their arrival to ensure they are not stolen, damaged, misplaced, or otherwise affected. Some companies are trying to improve visibility over their containers by installing GPS-enabled connected sensors to shipping containers, and then collecting the data on a number of factors—such as humidity, pressure, movement, and temperature.[26] These sensors are connected to a global network, allowing shipping companies and ports to track and allocate shipping containers to improve efficiency, cut costs, and protect their cargo.

For decades, ships have carried onboard sensors that collected data to help inform the specific ship's actions, but until recently this data was not used to optimize overall maritime operations.[27] Shipping companies have started to change this by adopting connected sensors, analytic software, cloud infrastructure, and mobile technologies to optimize their efficiency in handling cargo as well as monitor weather conditions across all ships in a network. For example, one mobile app, Route Exchange (REX), analyzes data from the ship's onboard sensors and provides the crew, other ships in the fleet, and land-based sea-traffic coordination centers with real-time information.[28] Similarly, Hyundai and Accenture are retrofitting existing ships with cloud-based sensors to track equipment as it travels, to issue real-time alerts, and aid in predictive maintenance.[29]

Ports have also started to adopt connected devices into their processes, such as smart-ship management, container tracking, intelligent warehouse management, port equipment monitoring, engineering equipment asset management, and others.[30] In the future, it will be more common for ports and harbors to be connected to ships and their containers to better manage trade flows, reduce theft, ensure ships spend less time idling, and allow companies to plan their shipments more efficiently. Furthermore, ports and harbors are teaming up with governments to reduce the amount of pollution in waterways by using technology advances to collect and analyze real-time data about pollution.[31]

Waste Management

According to the World Bank, urban solid waste is estimated to grow from 1.3 billion tons in 2010 to 2.2 billion tons by 2025, and the annual cost of waste management will rise from $205 billion to $375 billion.[32] To manage this increase, waste-management organizations have begun incorporating digital technologies.

Waste-management organizations (public and private) are using real-time analytics and IoT (Internet of Things) to derive insights and visibility into operational processes to boost productivity. Traditionally, when cities plan their trash collection, the number of bins they offer and the number of vehicles they deploy are estimated from the population size. However, this estimate is often wrong, which leads to either poor service or higher costs.[33] But with sensors placed on trashcans and recycling bins, waste management organizations are now able to use real-time data streams and algorithms to optimize the number of vehicles, their routes, and container locations.[34] For example, in 2014 Barcelona, Spain, placed monitoring sensors in its recycling and trash bins so that the city does not have to waste resources sending trucks to empty trash bins. The city estimated that it would save as much as 3 billion euros ($4.1 billion) over the next decade through increased efficiency.[35]

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Cities can use the data collected from these sensors to optimize waste pricing strategies. Traditionally, the price structure for waste management has been a fixed fee, which did not differ between heavy and light producers of nonrecyclable, non-compostable waste.[36] Because heavy producers do not feel the burden of generating waste under this model, it is difficult for municipal governments to reduce waste. As a result, to incentivize efficiency, many cities have started to experiment with pay as you throw (PAYT) programs that levy fees based upon the volume of nonrecyclable waste each customer produces.[37] Sensors placed in recycling and trash bins have helped municipalities, businesses, and residents track the amount of trash they produce. For example, in 2013 the City of Grand Rapids saw a 13 percent reduction in waste volume and a 67 percent growth in recycling volume from its IoT-enabled PAYT program.[38]

Once the municipal solid waste has been collected, digital technologies can help sort it to extract valuable materials. For example, the sorting company TOMRA offers automatic sensor-based sorting systems to separate all varieties of complex refuse, turning a jumble of plastics, glass, and even dirty municipal waste into a sorted marketable output.[39] Governments and utilities can then repurpose this output. For example, the Port of Rotterdam in the Netherlands works with AVR, a European waste and power company, to convert incinerated household waste to steam, heat, and electricity.[40] If a municipal solid-waste utility can use advanced sorting and smart analytics to recapture value from many waste products, then they can eliminate risks, reduce costs, and generate jobs.

Utilities can also use sensors to better manage landfills and protect the environment. For example, remote sensors can be placed around landfills to monitor for groundwater contamination and gas emissions, and to ensure regulatory compliance.[41]

Movement of People

A variety of infrastructures enable the movement of people for work and recreation.

Bicycles/Pedestrians

Digital technologies create opportunities to improve nonmotorized transportation, particularly in urban environments, by making it more convenient, safer, and more accommodating for people with disabilities.

Many of the digital transportation infrastructure benefits conferred on automobiles also apply to cycling and foot traffic. In Copenhagen, for example, where half of all residents commute by bicycle, the city is installing 380 smart traffic signals that can identify and prioritize cyclists to make their commutes faster.[42] The signals communicate with sensors that detect the number of cyclists approaching an intersection and can extend a green light to accommodate a large number.[43] Additionally, the lighting changes are programmed to allow "waves" of cyclists to travel certain corridors of the city without stopping and will adjust this timing automatically based on data from traffic cameras that estimate cyclists' speeds.[44] The city expects these changes to reduce travel times by 10 percent, and the added convenience will likely encourage others to commute by bike rather than drive or use public transportation.[45]

Digital transportation infrastructure can make public spaces more accessible for pedestrians, particularly the blind.

Also in Copenhagen, as well as in cities including Miami, Glasgow, and Los Angeles, city officials are piloting smart streetlamps equipped with sensors that can automatically detect cyclists and pedestrians, brightening as they approach and dimming after they pass.[46] These smart lamps allow cities to increase safety for pedestrians and bicyclists travelling at night while also saving energy.

Digital transportation infrastructure can make public spaces more accessible for pedestrians, particularly the blind. Bluetooth-enabled beacon technology distributed throughout an environment can communicate with a pedestrian's smartphones and provide navigation queues based on the user's location. Transport for London is piloting such a system, called Wayfindr, which relies on Bluetooth-beacons throughout subway stations to provide users with vision impairments audio-directional queues via their phones to help them navigate the station.[47] San Francisco Airport is also testing a Bluetooth-beacon system to aid blind travelers that can provide directions as well as information about points of interest, such as the nearest power outlet or coffee shop.[48] As this technology matures, cities and businesses could also use it to provide directions in multiple languages to make public and private spaces more accessible to nonnative speakers.

Roads, Bridges, and Transit

ICT is likely to emerge as the major tool to solve surface transportation challenges over the next several decades, as an "infostructure" gets built alongside countries' physical transportation infrastructure.[49] And while information technology is in the process of rapidly transforming the vehicles that travel on a nation's roadways—the advent of driverless cars and other autonomous vehicles (e.g., trucks and buses)—perhaps the most visible example of this information technology is also actively transforming roads, bridges, and ancillary highway infrastructure (e.g., traffic lights and toll stations). These technologies, collectively known as intelligent transportation systems (ITS), enable all infrastructure elements within a nation's transportation system—the roads, bridges, traffic lights, toll booths, message signs, etc.—to become intelligent by embedding them with sensors and empowering them to communicate with each other through wireless technologies. Together, these technologies are giving rise to roadways that are smarter, more efficient, safer, and more durable than existing highway-transportation infrastructure and which will transform how users consume and pay for transportation.

First, digital technologies have transformed charging and payment for road use. An increasing number of cities—including Jakarta, London, Oslo, Singapore, and Stockholm—have implemented congestion pricing systems, charging for entry into urban centers, usually at certain peak hours, as a means not only to reduce congestion but also to generate needed resources to fund public transportation and to reduce vehicles' environmental impact. For example, in Stockholm, automatic (license) number plate recognition (ANPR) technology, located at unmanned electronic control points ringing Stockholm's inner city, are used to levy a tax on vehicles entering and exiting the inner city when congestion is highest. Stockholm's congestion pricing system has yielded significant benefits, including reducing traffic congestion and carbon emissions more than 20 percent.[50] As half the world's population now lives in urban areas, some economists believe that urban congestion and emissions will be virtually impossible to reduce without congestion pricing.[51] Wider deployment of congestion pricing systems could have a significant impact on the United States: Economists estimate that if congestion pricing were used in just three to five major American cities, it could save as much fuel as has been saved with the fuel economy standards for light vehicles in the United States.[52] Further, it is estimated that broad use of congestion pricing on America's interstates and other freeways would reduce vehicle miles traveled by 11 to 19 percent.[53]

High-Occupancy Toll (HOT) Lanes—lanes reserved for buses and other high occupancy vehicles but that can be made available to single-occupancy vehicles upon payment of a toll—are another ITS-enabled mechanism to combat traffic congestion. The number of vehicles using reserved lanes can be controlled through variable pricing (via electronic toll collection) to maintain free-flowing traffic at all times, even during rush hours, which increases overall traffic flow on a given segment of road. For example, Orange County, California, found that, while HOT lanes represent only one-third of its highway lane miles, they carry over half the traffic during rush hours.[54]

Information technology is also transforming the once-mindless traffic light, giving rise to intelligent signals that adjust in real time to traffic conditions so that travelers don't have to wait at a light when no other vehicles are present or so that an ambulance can induce signals to switch to green (and opposing lights to red) as it speeds toward its destination.

Signal-light optimization can improve traffic flow significantly, reducing stops by as much as 40 percent, cutting gas consumption by 10 percent, cutting emissions by 22 percent, and reducing travel time by 25 percent.[55] A 2014 report by the Intelligent Transportation Society of America, *Accelerating Sustainability: Demonstrating the Benefits of Transportation Technology*, concluded that widespread deployment of these types of infrastructure and systems operations tools—particularly in the form of real-time adaptive traffic-signal control and synchronization, electronic toll collection, and incident management—could save the United States 119 million barrels of oil and 19 million metric tons of CO_2 over a 10-year period.[56]

Deploying digital roadway infrastructure—such as electronic toll collection, HOT lanes, ramp meters, and smart traffic lights—as part of a comprehensive region-wide ITS deployment can generate a significant positive impact for communities. For example, a 2009 Reason Foundation study found that reducing congestion and increasing travel speeds enough to improve access by 10 percent to key employment, retail, education, and population centers within a region increases regional production of goods and services by 1 percent. The study reported that achieving "free-flow traffic conditions" around key urban and suburban destinations in eight U.S. cities—Atlanta, Charlotte, Dallas, Denver, Detroit, Salt Lake City, the San Francisco Bay Area, and Seattle—could boost the economies in those cities by $135.7 billion and generate close to $9 billion in new tax revenues.[57]

Endowing the transportation infrastructure at key roadway intersections with intelligence could play a significant role in reducing vehicle and pedestrian accidents. For example, so-called cooperative intersection collision avoidance systems (CICAS), a form of vehicle-to-infrastructure (V2I) integration, could be incorporated into traffic lights (or other roadside devices), which would recognize when a collision between two vehicles appeared imminent (based on their speeds and trajectories) and would warn the drivers of an impending collision—or even communicate directly with the brakes to stop the vehicles.

A related V2I application called intelligent speed adaptation (ISA) aims to assist drivers in keeping within the speed limit by correlating information about a vehicle's position (for example, through GPS) with a digital speed limit map, thus enabling the vehicle to recognize if it is exceeding the posted speed limit.[58] The system could either warn the driver to slow down or slow the vehicle through automatic intervention. France has developed an ISA system that automatically slows fast-moving vehicles in extreme weather conditions, such as blizzards or icing.[59] ISA field trials have taken place in a number of European countries, including Belgium, Denmark, Britain, Finland, Germany, France, Hungary, and Spain.[60] European studies of ISA have found a positive effect on safety and a reduction in fuel consumption. The province of Victoria, Australia, is testing a system in which trains could remotely and autonomously brake vehicles attempting to cross their path at railway intersections.[61]

Digital infrastructure will also help maximize the use of existing transportation infrastructure and even improve its maintenance and repair. For example, a number of U.S. cities and states have developed innovative technology applications that improve the performance of transportation networks, enhance their safety, and streamline infrastructure repairs. For instance, Boston created Street Bump, a smartphone application that identifies potholes from cars' experiences driving over them; the app automatically relays these potholes' locations to the city transportation department. As Rosabeth Moss Kanter writes, Street Bump makes "your car and your phone allies in road repairs."[62] Another example is SF*park*, a parking management system developed by the San Francisco Municipal Transportation Agency and deployed at 7,000 of the city's 28,800 metered spaces and 12,250 spaces in 15 of 20 city-owned parking garages; the app tracks open parking spots and sets prices dynamically according to availability and demand.[63]

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Digital technologies will also help make the roads and bridges themselves smarter: that is, aware of their surrounding environmental and traffic conditions, and even the state of their own operating condition. Every year bad weather leads to slippery or icy conditions (e.g., black ice a driver can't see) that cause 1.5 million accidents and over 7,000 fatalities on America's roadways.[64] But new technologies can help detect (and in some cases, even remediate) these dangerous roadway conditions. For example, the Finnish company Vaisala has created an advanced system that can be embedded into pavement that measures what's on a road's surface in terms of ice, snow, frost, or water. Vaisala's sensors use infrared lasers to ascertain a road's surface temperature and state and wirelessly transmit that information to traffic management systems (e.g., to those dynamic messaging signs that provide motorists with real-time traffic information), thus alerting motorists to hazardous roadway conditions in real time. In the future, with vehicle-to-infrastructure systems in place, this information could be transmitted directly to the vehicle.

Similar to Vaisala's road sensors, new piezoresistive sensors (sensors that measure changes in electrical resistance) can be embedded in concrete in order to monitor stresses on bridges (and conditions on the bridge roadway), thus contributing considerably to enhancing bridge safety.[65] The sensors, connected wirelessly to the Internet, enable traffic managers to understand what kind of load a concrete bridge can carry and how durable the bridge is. The stress sensitivity of these piezoresistive sensors is 100 times greater than that of traditional sensors, allowing them to provide engineers with a continuous stream of accurate, real-time data about the health of the bridge structure.[66] Moreover, in the event of an earthquake or other natural disaster, the sensors can assess the bridge's dynamic performance, and, afterward, help to determine the residual capacity of the bridge.

Moreover, physical sensors embedded in or near roadways continue to be an important source of information about real-time traffic conditions (even if such data is being increasingly collected from the vehicles themselves, or the mobile phones of their occupants).[67] Providing real-time traffic information is vital to ensuring that motorists take the most efficient route to their destination (or switch their mode of transportation, if necessary). If the United States were to implement a real-time traffic system management information program in all states and the nation's 50 largest metropolitan areas, the U.S. Government Accountability Office (GAO) estimates that the present value cost for establishing and operating the program through 2018 would be about $1.2 billion. However, the present value of total cost savings due to benefits to mobility, the environment, and safety would be about $30.2 billion, reflecting a $29 billion benefit.[68] This works out to a benefit-cost of ratio of 25 to 1 for making real-time traffic information available to U.S. drivers nationwide. The GAO estimates such a system would deliver savings in incident delays of about 321 million hours annually, reduce annual fuel use by 11 percent, and reduce annual carbon monoxide, hydrocarbon, and nitrous oxide emissions between 10 and 16 percent.[69]

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In summary, the impact of digitalization on America's roadway is only starting to be realized. Investment in intelligent transportation systems should continue to be a priority in the financing of America's transportation system.

Aviation

Aviation, like oceangoing ships, does not rely on infrastructure to travel, as planes fly in the atmosphere. However, there are supporting infrastructures that makes it easier for planes to fly, such as the radar tracking system. While this system has safely guided aircraft for decades, imprecision and gaps in radar coverage have constrained airport and airspace capacity, and prevented the adoption of more efficient flight procedures and paths.

In the United States, the Next Generation Air Transportation System (NextGen) is the transformation and overhaul of the National Airspace System (NAS) from a ground-based system of air-traffic control that uses radar surveillance and analog communication to a satellite-based system of air-traffic management that uses digital communication. NextGen will update outdated weather-monitoring systems and significantly improve safety, capacity, and efficiency on runways and in the nation's skies while reducing fuel use, carbon emissions, and noise.[70]

NextGen will rely more heavily on satellite Global Positioning System (GPS) tools for surveillance and navigation, and on digital signals and interconnected computer systems for communications. The surveillance technology that the Federal Aviation Administration has adopted, called Automatic Dependent Surveillance-Broadcast (ADS-B), enables aircraft to determine their own location with a high level of accuracy and precision and then continuously broadcast that location along with the aircraft's identity, speed, altitude, and course to other aircraft and ground stations. The ability to more easily, accurately, and precisely identify aircraft flight data enables air-traffic controllers to better manage aircraft in flight, including reducing the required distance between aircraft and enabling more "as the crow flies" shorter routes. This technology also improves collision-avoidance capabilities and enhances safety over oceans and other areas that currently lack ground-surveillance coverage.

NextGen will also help avoid weather-related delays, which are currently the source of 70 percent of aircraft delays.[71] While some weather-related delays are unavoidable, many are due to failures and delays in processing or relaying weather data. One of the existing system's shortcomings is that there are multiple sources of weather information, none of which provide a holistic view of what aircraft are likely to encounter along their routes. The NextGen weather system will collect data from all major federal and commercial weather databases, consolidate and filter that data, use models to provide short- and long-term probabilistic forecasts, and then transmit forecast information to aviation decisionmakers and system users on a single network.

Finally, NextGen will help improve the safety and efficiency of communications between aircraft and air-traffic control centers, which is currently conducted primarily by analog voice communications technology. These communications, however, are labor- and time-intensive and rely on repetition of messages between pilots and controllers to minimize miscommunications. Digital data communication, on the other hand, can eliminate these sources of error. Furthermore, it is less labor intensive, increasing controller productivity, and nearly instantaneous, enabling air-traffic control to reroute aircraft much more quickly in response to changes in weather or traffic conditions. For example, the NextGen "Voice Switch" program will create a flexible voice communication system that will no longer require aircraft and controllers to be in close proximity.[72] This flexibility will help ensure that air-traffic control centers in one location can call upon underutilized staff in another to help handle workload spikes, which would otherwise have resulted in aircraft congestion and delays.

Other countries are also working to update their global flight infrastructure. For example, the European Union is teaming up with the United States to ensure seamless air-traffic services by making its air-traffic management system—called Single European Sky ATM Research (SESAR)—interoperable with NextGen.[73]

NextGen provides cost savings for the U.S. economy. The FAA estimates that failure to implement NextGen would cost the U.S. economy $22 billion a year in lost economic activity by 2022 due to delays and reduced air-traffic capacity.[74] NextGen deployment and implementation has begun across the nation, and as more airports and airlines adopt the system, net benefits will be greater.

Movement of Information

From the semaphore to the telegraph, from Ma Bell to high-speed broadband—innovations in the movement of information over distance is one of the most important drivers of productivity growth. Today, many communications systems that were separate in the past have converged on networks communicating using Internet Protocol (IP). The infrastructure underpinning IP communications is best understood as falling into two categories: fixed and mobile.

Unlike many areas of digital infrastructure, which have historically been associated with a government role—highways, water systems, etc.—U.S. telecommunications infrastructure since the invention of the telephone has largely been provided by private-sector providers in a regulated context. However, because of convergence—between cable TV and traditional wireline telephone systems to provide broadband and increasingly with 4G LTE wireless, broadband, either fixed or mobile, is not a monopoly, and the United States and most developed nations have rightly relied on private sector competition to drive progress.

Fixed Broadband

Over the years, communication networks have converged onto internet-protocol (IP) networks that use software to transform the digital bits they transmit into applications (e.g., voice, video, data). Over the last 15 years or so, digital networks have become "broadband," always on, fast networks. There are three general technologies for mass-market fixed broadband: various flavors of Digital Subscriber Line (DSL), cable modem, and optical fiber. DSL relies on the so-called "twisted pair" copper wires of the legacy telephone network, whereas coaxial cable was deployed to deliver cable television. Although these networks were developed for different uses, innovations have allowed them to be repurposed for broadband Internet access. Copper wires are somewhat limited, in that the rate at which they can transmit information drops quickly over distance—an acute problem in nations with large rural populations and suburban sprawl. In reality, both cable and copper networks are hybrids, with the core of the network and some "tendrils" to the edge having been replaced by newer fiber optic technology. Especially compared to DSL, fiber offers significant advantages, including higher, symmetrical data rates with lower operating expense, so new networks are generally built with fiber, and older networks are being replaced where it is cost effective.

NextGen will update outdated weather monitoring systems and significantly improve safety, capacity, and efficiency on runways and in the nation's skies while reducing fuel use, carbon emissions, and noise.

In the United States, in no small part due to the initiative of Google Fiber and the follow-through of the Gig.U project, and developments of new generations of broadband technology, a "Game of Gigs" has been sparked in the broadband industry, with more and more extremely high-speed networks being announced.[75] For example, for cable broadband, the shift from DOCSIS 3 systems to 3.1 will mean increases in throughput speed of up to 10 Gbps.[76]

Mobile Broadband

Consumers and businesses are increasingly accessing the Internet through mobile devices. With their ease of use, additional sensors and capabilities, and rapidly growing scale of adoption, smartphones are quickly becoming the predominant innovation platform of today. In addition to the smartphone devices we are familiar with, wireless Internet access is also enabling a boom in machine-to-machine or Internet of Things (IoT) communications.

U.S. consumers and businesses place tremendous value on mobile services. One analysis estimated that the $172 billion spent on mobile services in 2013 generated about $400 billion in total spending due to the multiplier effect.[77] Wireless services also touch a number of different sectors, enabling innovation throughout the economy. Take, for example, agriculture, where IoT devices will soon be leveraged to monitor many different aspects of agricultural processes. By some estimates, IoT and analytics will soon save 50 billion gallons of fresh water a year globally.[78]

Wireless Internet access is quite similar to fixed access, because wireless devices are generally only wireless for several hundred feet at most. Whether it is a mobile carrier or home WiFi connection, wireless networks try to get data into a wire as quickly as possible. It is these last distances, where mobile networks rely on radio spectrum, that make wireless networks relatively more capacity constrained compared with wired networks.

In the context of wireless policy, "spectrum" is shorthand for a portion of the broader spectrum of electromagnetic radiation that has properties useful for wireless communications applications. Spectrum has to be managed to reduce the possibility of interference since these signals travel through the air.

One of the most important tools in spectrum management is the license. Licenses are subject to a variety of service rules, but confer exclusive rights on a license-holder—such as a mobile carrier—to a defined band of spectrum in a given area. Spectrum licenses then allow operators a clean environment and flexibility to build their radio architecture as they think best. Over time, the industry develops better technologies to transmit data through the air, with the current standard, LTE, representing a significant improvement over the prior 3G standard. The next standard, termed 5G, promises to provide at least an order of magnitude increase in speeds and throughput.

Another important tool to ease access to mobile broadband is unlicensed spectrum. Unlicensed spectrum allows any equipment that meets basic technical requirements to use certain frequencies, allowing for widespread use of technologies like WiFi and Bluetooth. Ideological wars are waged over which tool is better for increasing access to mobile broadband—licensed or unlicensed spectrum. By now it is clear that both models have advantages and disadvantages, and the best approach is a mix of both.

When it comes to spectrum, the important point is simply that more of it needs to be allocated to broadband, as demand for mobile services is virtually insatiable. Cisco estimates that in 2019 U.S. mobile data traffic will be equivalent to 210 times the volume of mobile traffic 10 years earlier (in 2009), and spectrum is a major pinch point in meeting this demand.

To this end, many nations have made it a major goal to find additional spectrum to allocate to mobile broadband. The Obama administration aimed to make available a total of 500 megahertz of spectrum suitable for wireless broadband by 2020.[79] While the administration has made excellent progress, we are behind schedule to reach this target.[80]

But mobile isn't only about spectrum. Similar to the wired context, access to rights-of-way, conduit, and utility poles can go a long way in facilitating wireless equipment installation and expanding wireless broadband. As it stands, building a new tower or simply collocating an antenna on an existing structure can be a lengthy, involved process. New tower construction generally requires local approval, compliance with the National Environmental Policy Act, compliance with the National Historic Preservation Act, notification to the Federal Aviation Administration, and registration with the FCC.[81] Streamlining these processes as much as possible will see additional gains to the U.S. mobile infrastructure.

Benefits of Digital Infrastructure

Numerous studies have shown that ICT provides considerable economic benefits, especially in driving productivity.[82] As such, it should not a surprise that transforming traditional infrastructure into digital infrastructures (while also expanding pure digital infrastructures) will also provide significant benefits. There are four key kinds of benefits: the ability to bring to bear market forces to more aspects of infrastructure; improving the quality of infrastructure services by making infrastructure "smarter"; improving efficiency and cutting costs; and, finally, bringing real-time insight to bear.

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Harnessing Market Forces

Digital infrastructure allows infrastructure providers to more easily bring market forces to bear. Historically, markets only work effectively when there are accurate price signals and transaction costs are low. Smart infrastructure enables the easy collection and analysis of data that can allow services to be more easily priced, ensuring that supply and demand are more closely and dynamically aligned.

A case in point is smart-metering technology. Because analog meters were read only occasionally, utilities had difficulty adjusting prices to changes in demand and supply. And this meant that users had no incentive to use electricity more efficiently. But with smart meters, electricity providers can adjust pricing to correspond better to supply and demand, primarily usage during off-peak hours (11:00 p.m. to 7:00 a.m. and weekends) and peak hours (weekdays from 3:00 p.m. to 7:00 p.m.).[83] And with more granular data about usage, electricity providers can employ this model to protect against dangerously heavy strain on the power grid that could cause service disruption and costly repairs. For example, DTE Energy, which serves southeast Michigan, has developed a pricing model that only goes into effect during periods of extremely heavy strain on the power grid, charging $1 per kilowatt hour, compared to 12 cents per kilowatt hour during peak hours.[84] Water, sewage, and other traditional utilities also benefit from digital technologies that generate data to support more accurate pricing models.

Pricing road use would significantly increase travel efficiency.[85] This is because drivers impose costs on others or on the system, and current road infrastructure systems do a poor job of charging users for these costs. The most important of these is traffic congestion. But with technologies, such as vehicle miles traveled systems, travelers can be charged a differential rate per mile depending on when and where they drive. Doing so will increase the efficiency of the overall road network.

Similarly, broadband providers typically charge subscribers flat rates based on the speed of their connections, but are increasingly experimenting with pricing models similar to those used by mobile carriers that more accurately reflect both a customer's willingness to pay for Internet and the availability of bandwidth. Known as usage-based pricing (UBP) or data caps, these models rely on tiered pricing for the amount for data a customer expects to use per month.[86] Under a flat-rate system, the lightest Internet users essentially subsidize the costs of the heaviest users, who may use dramatically more data yet still pay the same.[87] UBP shows promise to have the heaviest Internet users pay a more appropriate share of the resource they use, while the lightest users can pay a proportionally lower rate. Not only is this approach more economically efficient, but the potential for lower-priced plans could make broadband more accessible for low-income populations.

Enhancing Efficiency

Digital technologies also allow infrastructures to be used more efficiently. For example, the Electric Power Research Institute estimates that dynamic pricing and other smart-grid capabilities have the potential to deliver average annual economic benefits of $31 to $50 billion due to improved efficiency over the next 20 years.[88] For airlines NextGen is also leading to more efficient travel. NextGen reduces congestion by using greater surveillance and navigation precision to open up more flight paths that different aircraft can use simultaneously. These new flight paths allow aircraft to fly in a straight line from airport to airport, regardless of where ground beacons are located. They also allow aircraft to exit and enter the flight paths when they are closer to their departure and destination airports, reducing flight distances and time and fuel spent waiting for clearances.

Enabling Smarter Infrastructure Services

For most infrastructures, companies or governments built the infrastructure and then just let it operate. Whether it was operating well and how to optimize its performance were often afterthoughts. What condition it was in was much harder to determine.

Data generated by digital infrastructure creates valuable opportunities for providers to gain more accurate and timely insights about performance. This is particularly beneficial for services that rely on historically analog infrastructure that can now have a digital layer thanks to the Internet of Things, as embedded, networked sensors can generate data on aspects of services that have never before been reliably quantifiable.

For example, sensors embedded in transportation infrastructure can provide city managers and urban planners with valuable data about how well the infrastructure meets the needs of travelers and can also power analytical models that can ensure infrastructure-planning decisions are as effective as possible. For example, Palo Alto is piloting a system of hundreds of sensors deployed around the city to monitor parking spot availability.[89] City managers could use this data to power an app that allows residents to quickly identify nearby parking, and as the city amasses more data about parking-space usage, data analysis could help urban planners understand where additional parking spaces are needed or how roads leading into congested areas limit access. And the New Jersey Turnpike Authority (NJTA) has partnered with IBM to implement a traffic management program that analyzes data generated by over 3,000 sensors and cameras on the New Jersey Turnpike and Garden State Parkway to help reduce congestion.[90] When these sensors detect a crash, high traffic volume, or other factors that can contribute to congestion, the system notifies NJTA staff, who can then issue alerts to drivers recommending different routes and update speed limits and messaging on Internet-connected road signage, which can help prevent costly and time-consuming traffic jams.[91]

Digital infrastructure and enabled analytics can play a key role in wastewater infrastructure. For example, in 2011 the Environmental Protection Agency found that the wastewater system in South Bend, Indiana, was discharging 2 billion gallons of sewage into the St. Joseph River every year due to the system's limited capacity, creating a pressing public health risk and violating the Clean Water Act.[92] Instead of implementing costly capacity expansion projects, the city implemented an analytics system that monitors water levels in the wastewater system and automatically controls valves that can ensure water is only flowing to pipes that have capacity available. By making smarter use of the city's wastewater resources, the analytics system saved the city $100 million in capital expenses and reduced sewage overflow by 95 percent.[93] In Utah and Oregon, transportation authorities have implemented analytics systems that pull data from sensors in highways and weather reports to determine where to deploy road crews most effectively during inclement weather, increasing the efficiency of road-clearing efforts and reducing the number of crashes.[94] And in Greenwood, Indianapolis, sensors in traffic lights communicate with emergency-response vehicles approaching an intersection and ensure that fire trucks, police cars, and ambulances do not get stuck at red lights, which can improve response times and save lives.[95]

Smart infrastructure enables the easy collection and analysis of data that can allow services to be more easily priced, ensuring that supply and demand are more closely and dynamically aligned.

It is difficult to ascertain the full scope of the benefits that data analytics will be able to provide for digital infrastructure, as both the Internet of Things and many advanced analytics techniques are still emerging. For example, it has only recently become technologically and economically feasible to install hundreds of connected sensors throughout a sewer system or deploy algorithms that can reliably count thousands of cars in a video feed in real time. However, as these technologies mature and more infrastructure gains a digital layer, there is every reason to believe that more and more applications will be developed.

Providing Real-Time Insight

With traditional infrastructure, it is usually difficult, if not impossible, to gain insight into real-time conditions. One way providers traditionally find out about conditions is when the infrastructure fails: The bridge collapses; the pipeline bursts; or the electricity blacks out. Applying a digital layer to infrastructure allows for real-time insight into performance, which can generate substantial economic and public safety benefits through preventative maintenance and early warning systems.

When a bridge collapses, it is usually the result of years of accumulated deterioration caused by heavy use, weather, shifting landscapes, or a variety of other factors—all of which create measurable structural changes. By embedding connected sensors throughout a bridge, civil engineers can monitor structural changes in real time and perform preventative maintenance whenever a defect arises but before it threatens the structural integrity of the bridge. The Jindo Bridge in South Korea employs such a system, which is expected to save millions of dollars by reducing the need for costly and unreliable manual inspection.[96] Similarly, in the Netherlands, sensor networks in levees automatically warn engineers about structural defects that could cause a breach up to 42 hours in advance, allowing them ample time to make emergency repairs.[97] Not only is preventative maintenance less expensive than rebuilding broken infrastructure, it also helps prevent catastrophic failure, which can cost lives, and avoid infrastructure downtime, which can be incredibly economically disruptive.

When a disaster is unavoidable, however, real-time infrastructure monitoring is crucial for early warning systems that can minimize the damage. For example, some Department of Veterans Affairs hospitals are now equipped with sensors that monitor the building's sway during an earthquake and warn hospital staff if it becomes dangerous enough that they need to evacuate patients.[98] Additionally, the EPA has launched an initiative to accelerate the development of low-cost aquatic sensors that can trigger an emergency warning whenever there are high levels of nitrogen and phosphorous build-up in a waterway, which can cause toxic algal blooms and the growth of deadly parasites that can cost $2.2 billion in damages per year.[99] And the National Aeronautics and Space Agency has sponsored a project called FireSat that will deploy a network of 200 satellites equipped with advanced imaging and infrared sensors to rapidly identify and track the spread of wildfires around the world as soon as they start, giving emergency officials advance warning if there is a need to evacuate and guiding firefighting efforts.[100]

Overarching Issues for Deployment

There are several overarching issues surrounding digital infrastructures, including ensuring cybersecurity, protecting privacy, and identifying the right balance between public and private ownership and provision.

Security

While digital infrastructure has always had to contend with cybersecurity vulnerabilities, these problems have been extended into the physical world with the increased integration of digital components with physical infrastructure. In particular, the integration of information technology with physical infrastructure has led to the development of industrial control systems, including supervisory control and data acquisition (SCADA) systems, which are used to remotely monitor and manage complex industrial processes such as electric power generation and wastewater treatment. Unfortunately, vulnerabilities in these systems can put the physical infrastructure itself at risk of sabotage by cyberattackers who may be able to disrupt essential services to millions of individuals.

These cybersecurity risks are not merely theoretical. For example, in 2015, almost a quarter of a million people lost power in the Ukraine after Russian hackers remotely shut down multiple substations across the country and disabled backup power supplies at power distribution centers.[101] The number of SCADA attacks worldwide has increased steadily over the past few years, growing from 90,000 attacks in 2012 to 160,000 in 2013, and then 675,000 in 2014.[102] Many of these attacks target the United States. In 2014, approximately 51,000 SCADA attacks were targeted at the United States.[103] Some of these attacks involve government-backed hackers going after critical infrastructure. For example, U.S. law enforcement discovered that Iranian hackers had seized control of a dam in New York for a number of weeks in 2013.[104]

Securing critical infrastructure is a task shared by the government and the private sector, which operates much of this infrastructure. Collaboration between the public and private sectors, such as through information sharing on cybersecurity risks and developing best practices, will be critical to predicting, identifying, mitigating, and recovering from cybersecurity intrusions and incidents that affect critical infrastructure. By forming strong partnerships across industry, law enforcement, and the intelligence community, those operating and controlling critical infrastructure can build smarter, more secure, and more reliable infrastructure.

Applying a digital layer allows for real-time insight into infrastructure performance, which can generate substantial economic and public safety benefits through preventative maintenance and early warning systems.

Privacy

Many types of infrastructure produce a significant amount of data. While much of this data is not about individuals—instead it is about the operation of the infrastructure itself, such as whether systems are running correctly or the availability of different resources—some data is related to individuals. For example, utility operators may track consumer usage data of a particular service, such as the amount of water, gas, or electricity consumed by a particular household. While much of that data will only be used in aggregate or after it has been de-identified, some of the data will be personally identifiable information. Unfortunately, U.S. policymakers have delayed the adoption of various technologies related to digital infrastructure in part because of the pushback these technologies have received from privacy advocates.[105]

Privacy objections to adoption of digital infrastructures occur as part of the "privacy panic cycle."[106] This cycle occurs when privacy advocates make outsized claims about the privacy risks associated with new technologies. But while these claims routinely fail to materialize, they still filter through the news media to policymakers and the public, leading to ill-advised policy responses that can slow adoption of beneficial new technologies. While these fears usually subside as the public becomes more familiar with the new technology, time and time again people fall into the trap of believing exaggerated claims about privacy risks for new technologies.

For example, privacy activists have fanned the flame of fear about the smart grid and smart meters for electricity.[107] Their concern is that analysis of data from smart meters might reveal certain personal information, such as the times of day when someone is at home, their household behavior, and the types of appliances they own.[108] This paranoia, which has been aided by media coverage, fueled efforts to derail smart meters' expansion in many places, including Florida, Maryland, Michigan, and Oklahoma.[109] And as of 2015, 17 states allowed customers to opt out of smart-meter installation, even though doing so imposes costs on the rest of the system's customers.[110] However, there is no evidence that any utility in the United States has ever used consumer data in a way that has caused harm. Instead, this data is used simply to provide consumers better quality service, enable new forms of dynamic pricing, and better manage electricity production and distribution. In fact, according to the Department of Energy (DOE) and the Smart Grid Consumer Collaborative, utilities have historically taken the job of protecting their customers' privacy very seriously.[111]

Similarly, some privacy activists have objected to intelligent transportation systems, including vehicle miles traveled (VMT) systems and vehicle-to-vehicle and vehicle-to-infrastructure systems, out of concern that the government, private-sector companies operating these systems, or car manufacturers would gain access to personal information about the movement of individuals, or that law enforcement might abuse the information for inappropriate surveillance. Again, these concerns have failed to materialize in practice.[112] Moreover, in the case of VMT systems, virtually all of the opposition is based on a faulty understanding of how such a system works. In a VMT system, the unit installed in the car uses GPS to know where the car is, and it uses this and other information to calculate what the car owner owes to various government jurisdictions. But no one knows where the car is, only the driver and the onboard device. And that device does not ever report trip information to the government. In this sense it is more private than the current EZ-pass system used on toll roads.

While many of these technologies, like VMT, will be inherently more privacy protective, some will have some tradeoffs. To the extent that there are legitimate risks to privacy, these concerns should be taken seriously and systems put in place to protect consumers against inappropriate use. However, privacy activists will often oppose new infrastructure that uses ICT simply because it collects data. In particular, they will oppose any project that involves the government or companies possibly collecting more data about individual. This type of opposition can limit many important advancements in using ICT to build smart infrastructure. Policymakers should recognize that as long as there are rules (public or private) in place to protect personal data, such as de-identifying data, these objections are without merit and should not be used to delay progress in pursuing digital infrastructure projects.

Public vs. Private Ownership

One of the core questions with regard to any infrastructure system or project is the appropriate mix of public and private involvement. Some projects are designed, built, owned, and managed by government, others by the private sector. Most involve a mix. While it is not possible to say a priori which is better—public or private ownership—all else being equal, private-sector ownership and operation brings several advantages, including a greater incentive for efficiency and innovation.

For telecommunication infrastructures, there is a long tradition, at least in the United States, of private ownership. The United States is fortunate that it already had two existing networks when broadband came along.[113] This has allowed for competition between different types of technologies to drive private investment into deploying and upgrading broadband throughout the country. This general approach to broadband policy—light-touch regulation of intermodal competition, rather than government building and owning communications' networks—has worked well.[114] According to Akamai's recent State of the Internet report, all 50 states, plus Washington, D.C., saw increases on a year-over-year basis in average connection speeds, and those ranked among the top 10 experienced double-digit gains.[115] The fact that the U.S. broadband industry has achieved competitive speeds while also maintaining low entry-level pricing is remarkable considering the hurdles we face with sprawling suburbs, rural states, relatively low levels of computer ownership, and relatively high rates of poverty.[116]

Despite these exciting developments, some continue to complain that consumers do not have enough choice when it comes to broadband providers. But competition in broadband networks is not an unalloyed good—more competitors in a given geographic market is not always better.[117] Having more firms with smaller market shares competing at low margins will necessarily raise overall production costs while reducing average firm revenues. The result, therefore, will be higher prices overall. As such, spurring more competition through proactive government subsidies or other policies is almost always less efficient in lowering prices and improving service than effective competition among fewer firms.

Market fragmentation is especially problematic when thinking about longer-term policy goals such as investment in infrastructure and research and development, introduction of new products and services, and offering such innovations at scale. In many cases, higher levels of concentration can better deliver such long-term benefits.[118] For these reasons, governments should not proactively subsidize the deployment of additional networks in areas that are already serviced.[119] Scarce subsidy dollars should be targeted at bringing service to unserved areas, not adding yet another competitor to areas with existing broadband service.

Two reasons why telecommunication networks have historically been private is that there was an easy way to raise revenue from user fees and the economics were such that private companies could own and operate infrastructure while still making a profit. Digital technology makes it easier to raise revenue from user fees on infrastructure, while at the same time making it easier to make a return on investment. Take the case of roads. There are few private highways because tolling is expensive and tolled roads often compete with free, government-owned roads. Moving to a VMT system would allow all roads to be priced (removing the free competitor), while at the same time lowering the transaction costs related to tolling.

Barriers to Wider and Faster Deployment

Despite the demonstrated results and even greater promise of digital infrastructure, deployment in many infrastructures has been slow. This is true for at least six reasons. First, as with any new technology, there is risk aversion, especially for governments who own or operate infrastructure. Second, operators, particularly government, lack digital technology experience. Operators are often more comfortable with concrete and steel than with chips and sensors. Third, many projects require an upfront allocation of capital that will more than pay for itself as the project generates benefits. But for some companies and governments, there is a lack of patient up-front capital available for such investments. Fourth, many of these technologies involve a whole set of coordination challenges. Smart-grid technology must be interoperable across utility grids, not just within one. The same is true for smart-city/smart-transportation technology. Moreover, there are chicken-or-egg issues involved. As more homes have smart meters, more appliances will be smart and able to operate in relationship to smart-meter signals. But since there are few smart meters, there are few smart appliances, and vice versa. Fifth, many infrastructure organizations and policymakers have been slow to embrace digital infrastructures because of pressure from privacy advocates who intentionally present misleading and frightening scenarios of how digital infrastructures will negative impact privacy. Finally, the proliferation of thousands of government and regulatory bodies makes it difficult to adopt common standards for technology and regulations.

For example, there are approximately 52,000 water utilities in the United States, and they vary in terms of size, ownership structure, and government oversight.[120] Private water companies often operate in multiple local jurisdictions and, in some cases, multiple states. State water commissions and boards regulate these utilities, and each may establish different requirements and conditions, which slow deployment.

Policies to Advance Digital Infrastructure

Because of the benefits of digital technologies, all infrastructure will become digital at some point in the future. But absent proactive public policies, this needed transition may well take a very long time. As a result, governments need to ensure that policies support the transition from traditional infrastructure to digital infrastructure.

Create "Digital-Friendly" Regulatory Policies

The robust deployment of hybrid infrastructure requires a smart and streamlined regulatory environment. Outdated and costly regulatory policies designed for the infrastructure of the 20th century may impair the development and deployment of infrastructure of the 21st century. Moreover, an excessively complex infrastructure-permitting process can delay delivery of new investments. For example, among the most significant barriers to widespread smart-grid deployment is the overall lack of a coherent and comprehensive national energy strategy aligned to existing policies and regulations. The current patchwork of policies and regulations is often characterized by overlapping mandates and conflicting goals. In addition, while the deployment of smart meters has accelerated in recent years, the approval by state public utility commissions of real-time or variable pricing has lagged dramatically—meaning that some key smart-grid benefits are not being exploited by those who have the capability. For virtually every digital infrastructure, there is a need to modernize existing regulations to reflect significant changes in technology advances and leading industry practices.

Agencies Should Develop Strategies for How They Can Support Digital Infrastructure in the Areas They Influence

Many state and federal agencies influence infrastructure either directly or indirectly. Each such agency should develop a strategy for how it can help speed the transition to digital infrastructures. For example, the U.S. Department of Transportation (DOT) should develop a comprehensive innovation strategy that articulates how it can promote the rapid deployment and adoption of proven intelligent transportation systems across the United States.

Increase Funding for Digital Infrastructures

For infrastructures where government is involved as an owner or operator, government should increase funding to transition to digital infrastructure. This means, for example, agencies like the Departments of Defense and Interior upgrading the infrastructures they are responsible for with digital technologies. It means that Congress should enact a new "Cement & Chips" funding approach that directs no less than 5 percent (approximately $2.5 billion) of the Highway Trust Fund (HTF) allocated to states to be devoted to digital and ITS-based infrastructure projects.[121] Congress should also ensure that ITS-related implementations are immediately eligible for funding under the existing highway transportation authorization. They should also tie a share of federal surface transportation funding to states' actual improvements in transportation system performance, which would promote an incentive to invest in cost-efficient digital infrastructure.

National governments need to also take a proactive role in creating national data and software systems that can easily be used by across the nation. In the United States for example, innovative applications have been developed at the local level. But, without coordination and support, these applications do not scale to nationwide tools available to all. It makes little sense for individual cities to reinvent applications developed elsewhere if platforms could be developed to scale these types of solutions nationwide; policymakers should consider strategies to broadly disseminate these applications, as detailed in the recommendations section below.

For transportation, the U.S. Department of Transportation should undertake to scale innovative local software and app-based ITS solutions nationally, such as by supporting the provision of shared ICT infrastructure, such as cloud storage. Likewise, the Department of Housing and Urban Development should take the lead in organizing a national system on urban data. For example, planners and urban researchers would love to have data on pedestrian movement. One could imagine an app that collects movement anonymously and on an opt-in basis and then, based on the geocode, aggregates for metros or cities. Likewise, HUD could support standards that allow all city zoning maps to be digitized and put on an easy-to-use app. Similarly, the White House should organize a competition to identify the 20 best such applications and task a nonprofit, such as Code for America, to take applications initially developed for individual cities and code them for use on a national basis.

Don't Let Privacy and Security Concerns Slow Deployment

While digital infrastructure projects manage and manipulate large volumes of data, realizing their promise need not require the sacrifice of privacy nor security. Policymakers should not let privacy advocates and others opponents of innovation slow the needed transition to digital infrastructures. Rather government should work in cooperation with the private sector to ensure that public policies support privacy and security in ways that enable innovation and allow the data generated by hybrid infrastructures to be used to create value for society.

CONCLUSION

Information technology is creating a smart world—from smart enterprises to smart schools to smart cities. It's time for societies to accelerate the creation of smart infrastructure. Doing so will generate an array of economic and social benefits. But without a clear and articulate goal of transforming traditional infrastructure into digital infrastructure, and the associated policies needed to do that, this needed transition will lag.

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