Title
Intelligent Transportation Systems and Infrastructure A Series of Briefs for Smart Investments

Authors
Bayen, Alexandre M.
Shastry, Shankar

Publication Date
2017-03-01

ITS Berkeley
Institute of Transportation Studies

Intelligent Transportation Systems and Infrastructure

A Series of Briefs for Smart Investments

Berkeley
UNIVERSITY OF CALIFORNIA

March 2017

Rendering: Airspace over UC Berkeley Campus, provided by UC Berkeley's Unmanned Autonomous Vehicles team

INTELLIGENT TRANSPORTATION SYSTEMS AND INFRASTRUCTURE: A SERIES OF BRIEFS FOR SMART INVESTMENTS

The last decade has witnessed an unprecedented convergence of communication, control, and sensing that can potentially transform transportation infrastructure and delivery. At the most basic level, efficient operation and maintenance of our nation's transportation infrastructure requires real time data exchange provided by intelligent transportation system technology. When implemented, these technologies have the potential to revolutionize the nation's economic vitality by moving people and goods more quickly, efficiently, safely, and at lower cost to consumers. The following briefs outline key policy and investment opportunities to support that vision:

Roads and Vehicles

Airports and Aviation

Project Management

Data and Broadband

ABOUT THE INSTITUTE OF TRANSPORTATION STUDIES

For nearly 70 years, since its inception in 1947, the Institute of Transportation Studies at the University of California, Berkeley, has been one of the world's leading centers for transportation research, education, and scholarship. The Institute operates on an average of $25 million in research funds each year. More than 100 faculty members and staff researchers and more than 100 graduate students take part in this multidisciplinary program organized into specialized research centers within the Institute.

CONTRIBUTORS

Alexandre M. Bayen, Director, Institute of Transportation Studies
Shankar Sastry, Dean of Engineering

Joe Butler
Alessandro Chiesa
David Culler
Mark Hansen
Ben McKeever
Laura Melendy
Michelle Moskowitz
Borivoje Nikolić
Brandie M. Nonnecke
Kristofer Pister
Jan Rabaey
Gireeja Ranade
Jasenka Rakas
Anant Sahai
Steven Shladover
Claire Tomlin
Karen Trapenberg Frick
Tom West

THE CASE FOR INTELLIGENT TRANSPORTATION SYSTEMS FOR ROADS AND VEHICLES

Intelligent transportation systems and technology provide a high return on investment, especially when incorporated as part of ongoing construction activities.

Efficient operation and maintenance of our transportation infrastructure requires real time data exchange provided by ITS (Intelligent Transportation System) technology. The cost to acquire and install this technology is roughly 5% of the overall construction budget if installed during construction. The ROI (measured in safety, travel time reliability, throughput and quality of life) takes less than 6 months in highly congested corridors. In addition, these transportation networks are now ready to support advances in automated and connected vehicles and in shared demand management approaches. All construction projects should be required to install ITS elements.

These ITS elements, a specialized subset of the Internet of Things (IOT), include congestion sensors, structural integrity monitoring, fiber communication, high resolution video, vehicle to infrastructure data exchange, intelligent traffic signals, special use lane management, emergency vehicle route clearance, safety guidance and message presentation.

ITS technology lets us know what is happening on our highways, arterials and bridges so that we can manage and maintain them. This technology ensures maximal return on investment for the large investments required to expand, upgrade and remediate our transportation infrastructure.
In detail, ITS Technology ensures that:

- US infrastructure is ready to support connected and automated vehicles, shared services, and, if planned, electrification.

- The nation practices performance-based management, ensuring that congestion is reduced, roads are safer, and that all future connected and automated vehicles do not end up stuck in the same traffic congestion patterns as conventional vehicles are today.

- Sufficient data is available to understand the actual performance of infrastructure investments in order to ensure that every funded project lives up to its advertised performance.

- Infrastructure is properly monitored in support of a robust maintenance program, so that, moving forward, America's infrastructure will never degrade to this extent or dangerous levels, ever again.

- Data is readily available that allows credible assessment of proposed Public-Private Partnerships (PPPs), and proper management of PPP revenue streams.

INFRASTRUCTURE SUPPORT FOR ROAD VEHICLE AUTOMATION

Much attention has been given to automation of road vehicles recently, but that attention has been almost entirely focused on the vehicles themselves, without regard to the roadway infrastructure on which they operate. The developers of automated vehicles have been reluctant to acknowledge their dependence on the infrastructure because developers are concerned about how to ensure deployment of a viable system if the public sector (i.e. public roads and highways) fails to deliver the expected infrastructure enhancements. Yet, the opportunities are greatly enhanced for vehicle automation to improve the safety, efficiency and traffic flow of the road network (and to deliver those improvements sooner) if the vehicles and the public infrastructure can operate as a well-integrated system. The rollout of vehicles with higher automation capabilities (the ability to operate without constant human supervision) will already be geographically limited because of the need for very detailed and carefully validated digital maps of all the locations where they can operate. If the mapping of those locations is accompanied by suitable physical modifications to the infrastructure, the automation systems will be able to deliver higher levels of performance and safety, sooner, and with less costly in-vehicle technology.

Three different categories of infrastructure enhancements need to be considered:

- low-cost electronic and road marking changes that can be applied throughout the road network,
- physical changes to urban roads to facilitate their use by low-speed automated vehicles; and
- fully segregated lanes for automated vehicles on high-speed freeways.

Electronic and marking changes. The integration of vehicles and infrastructure devices into a well-coordinated road transportation system will be facilitated by the deployment of 5.9 GHz DSRC communication devices at key locations throughout the road network, such as signalized intersections and freeway interchanges. These will enable two-way communication between the vehicles and traffic management systems so that they can maximize safety, efficiency and traffic flow. In addition, the visibility of the pavement markings and road signs need to be improved and standardized so that they can be more easily recognized by machine vision systems (which will also improve their visibility for human drivers).

Physical changes to urban roads. The first generation of urban automated vehicles have limited sensory capabilities and are restricted to low speeds and environments in which their interactions with other road users can be physically constrained. For these vehicles to provide useful transportation services, they will need some specialized road markings, curbs, signal-protected crossings, and barriers to safely separate them from manually driven vehicles, bicyclists, and pedestrians.

High-speed freeway changes. Automation has great potential to improve the safety, efficiency and traffic flow of trucks, buses and cars on freeways, but its ability to deliver these benefits is constrained by the disruptions and hazards introduced by conventional human-driven vehicles. Providing physical segregation between the lanes used by the automated vehicles and the conventional vehicles overcomes these hazards, enabling the automation systems to deliver their benefits earlier, without the added complications introduced by the need to safely accommodate the behaviors of unpredictable human drivers.

NEXT GENERATION ROAD INSTRUMENTATION FOR HIGH PERFORMANCE OPERATIONS

Background. The cost of road congestion in gross GDP in the US is in the billions of dollars every year, mostly due to impacts on services relying on transportation, and secondary effects associated with the inefficiency of the transportation network. Most of the traffic operations on freeways can greatly be improved with instrumentation. For most cities in the US, highway instrumentation dates back to the 1960s: loop detectors in the pavement. Most of these detectors are unreliable, and often fail (a 40% failure rate is common in most cities). With the explosion of video cameras enhanced by the expansion of the mobile phone industry, the US is entering a new era, in which it could lead by leapfrogging the current state of the art. The US could move to fully camera-based operations, as our current communication networks have the potential to provide ubiquitous coverage. This would empower the US DOT and State DOTs with unprecedented capabilities.

Objective. We recommend the US DOT provide a new video-based architecture for road monitoring. The goal of the architecture will be to provide ubiquitous visual sensing of the freeway network, leveraging the already existing communication network (LTE and soon 5G). By leveraging an existing communication infrastructure, and with the rapidly decreasing costs of cameras, the potential for revolutionizing traffic operations with this new monitoring is enormous. Artificial intelligence (in particular deep learning) has provided processing capabilities that can allow public agencies to benefit from the vast amounts of data enabled through this architecture.

Approach. We propose defining the architecture of a new generation monitoring system based on low-cost cameras connected to the existing cellular network. This approach will build on the very successful NGSIM pilot developed by the US DOT more than 10 years ago, in which high fidelity video data was collected and shown to provide the most insightful features about road traffic in the last decade, due to its richness and quality. Taking the original “pilot” to the next level, we will push the NGSIM paradigm to ubiquity, real-time and streaming data. We will build the proper real-time processing engines to support operations relying on this data. We will write specifications so the data can be used by real-time decision support systems in traffic control centers.

Expected impact. The impacts of this infrastructure will be (1) more efficient operations on a regular basis; (2) increased efficiency of the transportation network leading to reduction in costs of congestion (3) more resilient infrastructure in the face of large scale natural disruptions (hurricanes, snow storms, floods, heavy rains), and better management of both anticipated and unanticipated events such as city evacuations (New Orleans etc.); (4) national security: with ubiquitous monitoring of the major freeways and the backbone of the transportation network, our national agencies will be better informed of threats and responses in real time.

AN AIRPORT SYSTEM FOR THE 21ST CENTURY

The sorry state of America's airports has been widely observed by political leaders, journalists, policy analysts, engineers, and scholars. Most importantly, inconveniences are experienced daily by 2.2 million travelers. Renewing the nation's airports will at once improve the travel experience, reduce flight delays, improve safety, and demonstrate our commitment to an infrastructure befitting an advanced economy.

Carefully designed policies, plans, and programs to renew the nation's airport infrastructure can accomplish far more than produce gleaming terminals, expand airfield capacity, and improve ground access. Our goal must not be to match world-renowned but rapidly obsolescing airports such as Singapore Changi, Tokyo Haneda, or Munich, but to leapfrog them by building an airport system for the 21st century. Such a system, while still accommodating the air travel of today, must also allow for emerging vehicle types, new business models, and ease of use by an aging population. It must be resilient to contemporary natural and manmade threats. Its infrastructure design must be more 'elastic' and easily re-configurable in order to utilize latent capacity of the existing airport layouts, given that most airports in urban areas cannot physically expand their infrastructure. It has to be built in the most cost-efficient manner, using construction materials that are durable, smart, and energy efficient. Finally, it must be managed and financed in a manner that adapts best practices from around the world to the US setting.

A 21st century airport system must fully integrate unmanned air vehicles (aka drones). Not only must current restrictions on operations near airports be eliminated, the airports must also allow for connectivity between conventional aircraft flying longer routes and drones providing local delivery. While such local deliveries would initially involve cargo, it is likely that over the lifetime of these airports, the technology will prove sufficiently reliable to permit passenger access as well. Other models of access including the burgeoning ride-share sector, which may also feature flying cars within the next decade, must also be accommodated. In addition to permitting such services, the future airport system should benefit from them by enabling flight operators to change arrival and departure airports in near-real time in response to emergencies or demand-capacity imbalances.

Rising sea levels pose a substantial threat to many US airports. Thirteen of the nation's largest airports are prone to flooding as a result of a moderate to severe storm surge. Increased density and intensity of lightning strikes, which cause physical damage and disrupt operations, pose another threat. Investments to fortify airports against these hazards and in systems for effectively responding when damage does occur deserve high priority. Flight diversion strategies can be enabled by a highly adaptive system for airport access and egress that ride-share services can provide. Other innovative approaches, such as floating runways stabilized by advanced control systems, should also be considered. Finally, in addressing terroristic threats, the focus must shift to the safety and security of the entire airport system, rather than just terminal buildings.

A 21st century airport system can be privately financed and repaid from user fees in urbanized areas, although support from the public sector may be required elsewhere. Loosening of restrictions such as caps on passenger facility charges and limits on the use of market mechanisms to allocate capacity can increase revenue streams and supplant obsolete charging systems (for example, weight-based user fees). A major rationale for economic regulation and public sector control of airports is the threat of monopolistic behavior, which may no longer be valid in many regions. The competitive London airport model, in which each airport is under separate management, is worthy of consideration. While government oversight to assure safety, protect the environment, maintain flight operator access, and prevent monopolistic exploitation in some areas may still be needed, substantial deregulation will energize airport development.

INFRASTRUCTURAL DESIGN FOR DRONES IN LOW ALTITUDE AIRSPACE

There has been an immense surge of interest in using unmanned and manned autonomous vehicles (UAV) for civil applications. Through projects such as Amazon Prime Air, Google Project Wing, and Airbus's Project Vahana, many companies are investing heavily into drone services such as commercial package delivery, flying taxi service, aerial surveillance, emergency supply delivery, videography, and search and rescue. Other companies involved in drone development include Airware, Iris Automation, and Uber; in addition, this movement towards drones has been happening worldwide, in the US, Canada, China, and most recently the UAE. There is currently a tremendous and rapidly growing commercial market for drones in the US and globally.

Since drones are envisioned to fly in the low altitude space of about 200 to 500 feet, the allocation of this airspace resource must be done carefully to maximize safety, privacy, efficiency, and ease of human participation. As a result, new infrastructures are needed. We propose to develop tools for government agencies to establish such infrastructures in a principled way. Our tools will rely on a combination of systems analysis and publicly available data from sources including NASA, FAA, ArcGIS, and NOAA. In collaboration with NASA Ames and Armstrong Flight Research Centers in recent years, we have been designing low altitude airspace infrastructure. We have proposed the concept of air highways, or virtual pathways in the airspace. Air highways provide a scalable and intuitive way for managing a large number of drones. These paths can be updated in real-time according to changes in the airspace. Trunks and branches of air highways, similar to ground-based highway systems, naturally emerge.

For regional and city-level drone infrastructure, the next step towards a complete and practical UAV, infrastructure would be to consider multiple levels of air highways, possibly separated by altitude. The goals in the design of these highway networks include connectivity between cities, efficient and safe use of different altitude levels, and flexibility with respect to unknown or changing conditions in the airspace. Many practical details, such as the locations of and rules for intersections and exits, need to be designed.

For "last-mile" drone planning, one potential solution would be to use a priority-based method for reserving space-time for each drone. However, unlike traditional route planning methods that reserve a large block of the airspace for a long period of time, we believe that adopting a fine-grain space-time reservation would greatly improve throughput. Last-mile operations will involve drones flying in close proximity to humans and other important assets on the ground. Therefore, real-time data will be essential for assessing risks of flight routes. Data needed by drones and drone operators for planning include city zoning maps, which provide priors for human occupancy; cellular traffic data, which can be used to infer human occupancy; and road traffic data, which is useful for predicting day-to-day human movement.
We will develop computational algorithms that provide ways of establishing these levels of infrastructure, allow ease of restructuring when necessary, and provide interfaces between the different levels. We will take inspiration from current air traffic control protocols and road networks, but design the low altitude airspace infrastructure in a principled and automated way that accounts for data such as terrain data from NASA JPL, population density data from ArcGIS, and wind data from the NOAA.

The intended customers of this innovation and associated software are any institutions that need to establish low altitude traffic rules, or monitor the status of air traffic, including government agencies as well as companies using the infrastructure.

MAJOR INFRASTRUCTURE: AVENUES TO IMPROVE COST ESTIMATES AND IMPLEMENTATION

Embedded in public policy proposals for new infrastructure projects is an optimism that infrastructure can be delivered quickly, on time, and on budget. Recent history of major infrastructure projects in the United States and worldwide—often called "megaprojects"—tells us that this could not be further from the truth. Projects take longer than expected and construction costs are higher than anticipated, even for projects that appear "shovel ready." Project sponsors also estimate financing costs decades in advance of project completion and typically do not adequately publicize these costs, which can double estimates.

Large-scale infrastructure endeavors often have characteristics identified by Karen Trapenberg Frick in her recent book on the new San Francisco-Oakland Bay Bridge as the "7 C's of Megaprojects."[1] They tend to be *colossal, costly, captivating, controversial, complex*, laden with issues of *control* between key actors, and in much need of *communication* between key actors, the media and the public. These characteristics complicate project timelines, cost estimates, and other outcomes. Avenues for performance improvement are to:

- Improve cost estimating methods by comparing the project under consideration statistically to numerous similar projects, particularly their cost and delivery timelines; and, including sufficient contingency estimates. Governments and researchers in the United Kingdom, European Union, Australia and the Asia-Pacific, look to this method called "reference class forecasting."[2] Augment this analysis with detailed comparisons of transaction costs, such as financing, legal, right-of way, and environmental processes.

- Work with the States to evaluate the potential for centralizing infrastructure delivery and financing. In tandem, the federal government should evaluate additional steps to improve use of risk analysis, independent external oversight, and peer review of projects across infrastructure types or at least within one sector such as transportation.

- Establish a clearinghouse with detailed information that would allow for rigorous comparative analysis of individual project costs, risk management, peer review processes, and project delivery methods of forthcoming projects. Then, the United States could learn from its experiences with major infrastructure investment and improve and innovate in future efforts.

- Consider a pilot program to incentivize the establishment of "innovation development centers" within projects and leadership academies. These would focus on spurring innovations and improving public agency staff capabilities to efficiently deliver projects, in partnership with private sector investors. Funding in part could come from industry partners, as has occurred with London's Crossrail megaproject.

---

[1] Trapenberg Frick, K. 2016. *Remaking the San Francisco–Oakland Bay Bridge: A Case of Shadowboxing with Nature*. Oxfordshire: Routledge; for other examples, see Poole, R. and P. Samuel. 2011. Transportation Mega-Projects and Risk. Reason Foundation Policy Brief, February 2011.

[2] Cantarelli, C.C. and Flyvbjerg, B., 2013. Mega-Projects' Cost Performance and Lock-In: Problems and Solutions. In Priemus, H. and van Wee, B. *The International Handbook on Mega-Projects*. Cheltanham, UK: Edward Elgar.

A RESILIENT CYBER-PHYSICAL INFRASTRUCTURE FOR TRANSPORTATION

Background. In the last ten years, all kinds of infrastructure and products have tremendously increased use of embedded wireless sensor devices, often referred to as the Internet of Things (IoT) or Network Embedded Sensors Technology (NEST). Streaming data collected by these sensors can be analyzed "in the cloud" using advances in "machine learning" to provide analytics for new services, such as ride sharing, route and traffic management, autonomous and semi-autonomous cars and trucks, and fleet management. The development of this "cyber" heart of the transportation infrastructure is one of the main societal challenges of our day. It is also the enabler of the "sharing economy" for transportation, which has already created innovative companies, such as Waze, Uber, Lyft, and Lyft.

Objective. While we are already seeing parts of the cyber-physical infrastructure combining analytics in the cloud with IoT sensor big data, there are several challenges as it relates to the safety of societal-scale transportation systems:

1. Difficult to build and configure. Large-scale cyber-physical systems need to be built by hand and then tested laboriously for correctness. We need more automated methods for building "correct-by-construction" large-scale transportation systems.
2. Fault tolerance. With large numbers of sensors in the wild, it is to be expected that some of them will fail. We need, nonetheless, to guarantee that the properties and extracted analytics are accurate even under faulted conditions. In particular, we need the transportation infrastructure to function even in the face of natural disasters such as partial flooding, and other inclement weather.
3. Cyber survivability. Each new cyber infrastructure introduces new potential vulnerabilities to cyber-attack. By building a taxonomy of attacks and defenses, we can create a transportation cyber infrastructure that is not only capable of withstanding attacks, but also has strong security and intrusion detection systems to deter attacks.
4. Learning. With a number of artificial intelligence, deep learning, and adaptive learning algorithms in various elements of the transportation infrastructure, we will need to provide human users with a consistent view of the automation, while simultaneously providing the automation with a consistent view of human behavior.

Approach. The approach we recommend is multi-disciplinary, combining the best of information and communication technology, with cyber security and high confidence design attributes. "High confidence design" is the ability to build systems that are correct by construction, fault tolerant, and resistant to cyber attack. A model-based design methodology to develop design tools and software is critical for all stakeholders to develop and evaluate new designs in a so-called "software windtunnel." Building high confidence into the operation of learning is another major design challenge for systems design, which spans model-based and data-driven approaches of deep learning.

In the construction of societal-scale cyber-physical systems, the design of mechanisms to take advantage of new analytics (e.g.,example Google Maps or new parking apps on smartphones) is critical to guarantee fairness, transparency, and accessibility by societal stakeholders for evaluation. In particular, we will need to provide opt-in privacy metrics to allow individual users to choose their levels of comfort. Mechanism design, including real-time pricing, is a sophisticated process involving an assessment of social justice and other qualitative issues (of a kind which are already encountered with simple congestion pricing).

Expected impact. A cyber-physical infrastructure is the key enabler for determining the future of mobility, using ride sharing, semi-automated cars, parking, and other new services that support societal efficiency while enabling privacy, security and resiliency of the infrastructure. The development of this cyber infrastructure will also foster creation of numerous start-ups and small businesses both on a regional and national level. Huge multipliers from robust and smart federal investment can result in a resilient infrastructure that will be both efficient and an economic spark plug for the nation.

A DATA INSTITUTE FOR NATIONAL INFRASTRUCTURE MONITORING

Background. Globally, the last decade has witnessed an unprecedented convergence of communication, control, and sensing in single platforms such as smart phones, sensor networks to equip various facilities, and vehicles. With new paradigms such as the Internet of Things, "the swarm," precision monitoring of national infrastructure is now possible, as new infrastructure is built, or existing infrastructure is upgraded. In many cases, this data is collected already, and in others, the cost of deploying infrastructure to perform monitoring comes at a fraction of the cost of construction. The US could greatly benefit from the leadership of a national infrastructure monitoring institute, with the mission of leading the nation's efforts to manage its infrastructure better.

Objective. The Institute for National Infrastructure Monitoring would have several missions. It would assemble the leading engineers, policymakers, elected officials, operational agencies in the US around an ambitious agenda: (1) define tomorrow's monitoring infrastructure for bridges, dams, buildings, roads, tunnels and other assets of value to the nation; (2) write implementation plans for how this new layer of infrastructure should be deployed as we rebuild our nation; (3) devise data analytics strategies to equip the backend computer systems that will manage the infrastructure data; (4) invent the tools that will enable policymakers to make more efficient decisions based on data, for example when to replace a part of a bridge, when to inspect infrastructure after natural (or man-made) disruptions, etc.

Approach. The proposed Institute will be led by top engineers in the US who have a track record of building large-scale monitoring systems (i.e. engineers from successful US companies, civil engineers, systems engineers, etc.). These experts will define a technology agenda to make our nation's infrastructure "smart." They will build a roadmap of priority assets that should be instrumented, and guide the public agencies in recruiting the proper experts to do it. It will assist with the directions the data analytics should take to provide the maximal value to the public agencies in charge of operations for these assets.

Expected impact. The impact of the Institute will be manifold. It will provide critical guidance to public agencies and elected officials when expertise is needed (e.g., testimony, decision on approaches to take for infrastructure). It will provide policy recommendations with concrete quantification of risk-benefits tradeoffs ("how much financial benefit is gained by the agency to upgrade one asset vs. another, and at what risk?"). The Institute will provide a global view of the state of our infrastructure to our leaders in real-time. It will provide the proper analytics tools so anticipatory policy can be devised, i.e., using forecast models, to understand when actions should be taken in the future for infrastructure management.

INVESTMENT IN BROADBAND INFRASTRUCTURE NECESSARY FOR OVERALL INFRASTRUCTURE RESILIENCY

Background. Advances in information and communication technologies (ICTs) hold great promise to enable efficient, cost-effective infrastructure systems and services that result in long-term resiliency. Intelligent infrastructure enabled through incorporation of the Internet of Things (IoT)--software and sensors embedded in physical infrastructure (e.g., bridges, roads, railways, dams, electrical grids) and connected to a network--are central to our nation's ability to handle current and future infrastructure demands. High-speed wireline and wireless broadband infrastructure is critical to the performance and impact of these data-centric systems. As such, it should be considered a core component of US infrastructure, vital to overall resiliency.

Objective. Intelligent infrastructure utilizes ICTs to monitor, predict, and respond to changing demands, environmental impacts, and structural degradation. Proactive and predictive insights gleaned through data collection and analysis lead to unprecedented efficiency gains. For example, researchers at UC Berkeley designed, tested, and validated use of a wireless sensor network to collect ambient structural vibrations on the Golden Gate Bridge to monitor structural changes of the bridge unobtrusively and at a lower cost.

Efficiency gains are not only found from application of ICTs within a sector, but can also be identified across sectors. Infrastructure systems are interconnected. Sustainable communities are enabled when insights from transportation demands are used to determine energy consumption needs and renewable alternatives. Healthy communities are enabled when water can be conservatively allocated while maximizing agricultural productivity. These cross-sector insights require empirical and applied research enabled through the instrumentation of infrastructure, data interoperability, and access to high-speed networks.

Approach. Intelligent infrastructure enables real-time monitoring of the structural health, changing demands, and environmental impacts of public infrastructure. We propose that federal infrastructure investments include wireline and wireless broadband infrastructure and support cross-sector research to validate intelligent infrastructure strategies, tools, models, and data collection and sharing processes. Additionally, research on tax incentives and models for city-level readiness (e.g., permit structures, access rights to conduits/poles, broadband conduit installation in highways, instrumentation of infrastructure) should be supported in order to better ensure resilient infrastructure development nationwide.

Expected impact. Intelligent infrastructure enabled through the nationwide build out of high-speed wireline and wireless broadband networks will streamline infrastructure development and maintenance, reduce deleterious environmental effects, and promote economic growth and the safety and wellbeing of communities. Most importantly, it will stretch and maximize the benefits of each federal dollar invested in new or improved infrastructure.

LOW-LATENCY BROADBAND WIRELESS NETWORKS FOR INDUSTRIAL AUTOMATION

Background. Modern automatic control systems, such as intra-vehicle communications and immersive computing applications, require the communication delays between the stimulus and the response to be on the order of milliseconds. This requirement comes from the stability of control loops and human perception. Industrial systems are largely implemented using physically wired systems to achieve an ultra high reliability (1 in 10^9 errors) specification along with the low-latency. However, wires have problems of their own—they and their associated connectors present robustness issues in industrial environments, and add weight to cars, airplanes and robots.

Objective. We propose the development of a scalable and secure network of wireless motes that support high reliability and guaranteed millisecond latencies. The proposed network employs relaying strategies to provide multiple paths for data to make its way from the controller to the actuators, increasing reliability. These networks can enable communication and control between vehicles in platoons, as well as other devices such as autonomous drones. Furthermore, the introduction of fast and robust wireless connectivity will increase the flexibility for innovative manufacturers to introduce new products or adapt existing designs. We propose developing protocols that can harvest diversity, time-synchronized networking, local caching, efficient and fast error-correcting, code-based discovery, and network coding to meet the required latency. The resulting short data packets, containing readings from sensors or commands to the actuators, such as position and velocity will reach the destination in guaranteed sub-millisecond time.

Approach. There are multiple layers to the development and deployment of these networks. First, we propose adopting specifications from wired industrial networks and autonomous driving as benchmarks, and to develop wireless protocols to meet them. We will mimic the end-to-end performance of a wired network (such as industry-dominating SERCOS III) in terms of latency and reliability. The proposed system is based on an information-centric swarm of devices at the fringe that utilize a scheduled (TDMA) MAC with simultaneous relaying to realize deterministic latencies. The envisioned distributed synchronization is resilient to network outages by leveraging wireless redundancy.

The network will address dynamic configuration, including rapid discovery, by relying on network coding as a mechanism for reliable content delivery without the need for fragile routing tables. We will adapt state-of-the-art machine learning and artificial intelligence technologies to be compatible with the communication and control frameworks. This will require a re-think of the traditional architectures for communication networks—the control and real-time nature of the application will have to be considered, and cross-layer design may prove beneficial. We will further aim to provide provable guarantees on the performance of the network and protocol.

To demonstrate the feasibility of our approach, we will build a network of motes, built on our own open-source processors running a real-time operating system, augmented with custom radio basebands that enable low latency with relaying capabilities.

Expected impact. With the rise of increasingly intelligent vehicles and transportation infrastructure, there is a very large market for technologies that speed up the development and deployment of such intelligently interacting systems. Industrial control is another very large market, and for both of these, communication is critical. Making communication wireless dramatically simplifies deployment of intelligence into manufacturing and transportation. For example, low-latency wireless networks enable dramatic weight reduction in aerial and land vehicles and their interaction with the traffic infrastructure. They also enable operation of systems with a human in the loop, embedded in a real-time system, with no perceived lag by the user. Beyond transportation and manufacturing, this is important in enabling diverse areas such as telemedicine, telepresence, entertainment, and gaming.