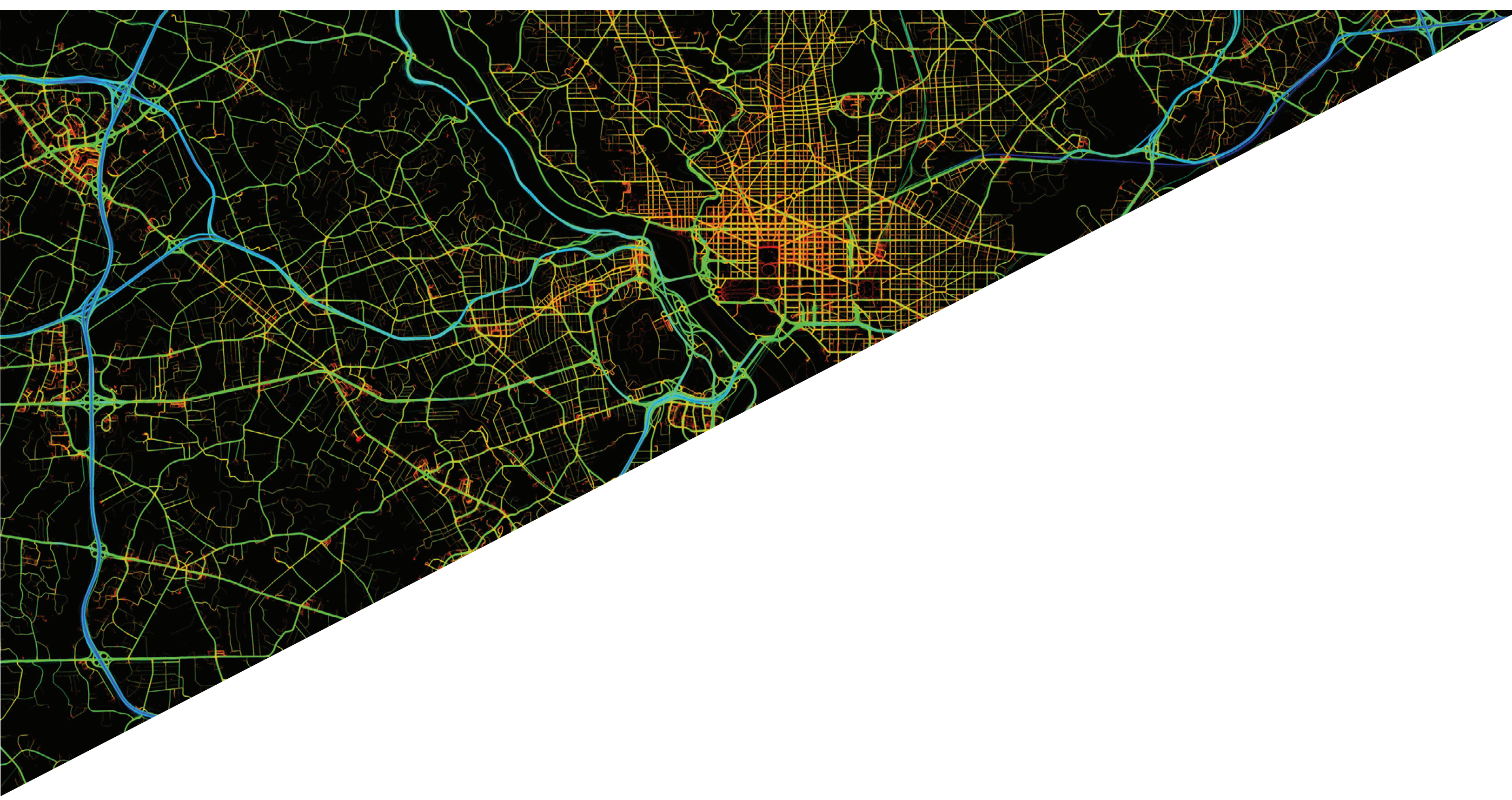
A Resilient, Equitable, and Smart Infrastructure System for the Next Century

Considerations for the Future of ARPA-I



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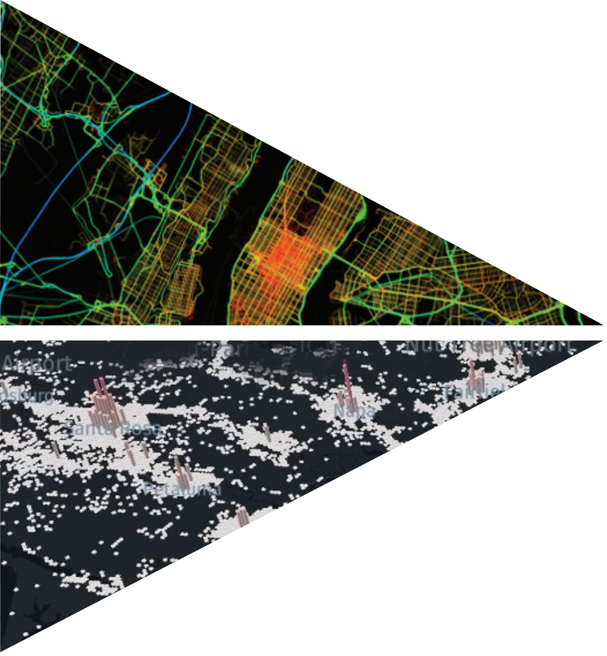
Berkeley Institute of Transportation Studies

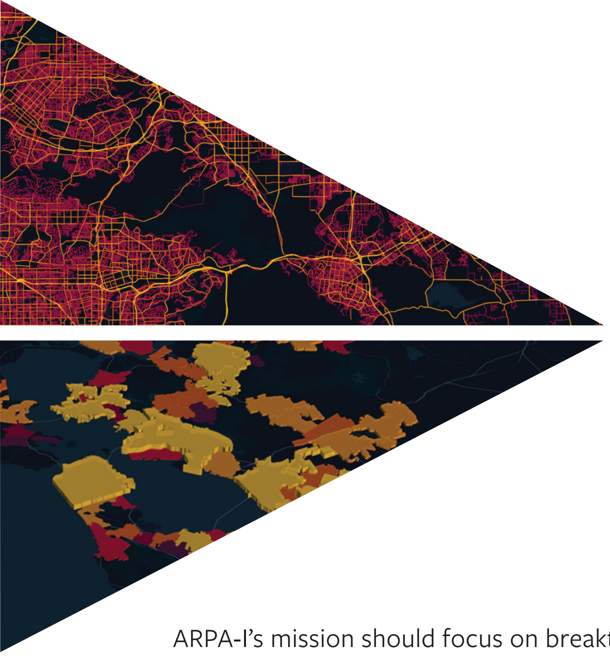


A Resilient, Equitable, and Smart Infrastructure System for the Next Century

Transportation infrastructure for the next century must be dramatically redesigned in response to the critical challenges related to carbon neutrality, sustainability, equity, and resilience. From planning and impact assessment to project delivery, maintenance, operations and reuse, each component and every step of the transportation value chain is ripe for significant transformation. Tomorrow's infrastructure will be built with carbon-neutral materials that are durable, smart, and energy efficient. Infrastructure designs must be more elastic and easily reconfigurable to take advantage of unused capacity of existing systems, allow for experimentation with new technologies, and be flexible given that infrastructure expansions may be difficult to achieve due to existing constraints. A forward-looking infrastructure system is also multimodal. It fully integrates emerging travel modes and relies on a different fuel mix to reduce or eliminate its carbon footprint.

Renewing the nation's infrastructure will improve the travel experience, reduce delays, enhance safety, and demonstrate our commitment to an infrastructure befitting an advanced economy. Yet, the value of this infrastructure has reach far beyond its role in enhancing the movement of freight and people. When implemented, the next generation of transportation infrastructure has the potential to revolutionize the nation's economic vitality and competitiveness while advancing sustainability and equity goals.

The announcement of the establishment of Advanced Research Projects Agency-Infrastructure (ARPA-I) opens extraordinary opportunities to support the transformation of transportation infrastructure for the next century. ARPA-I is a strategic initiative with the power to unleash technological innovations with global impact. The following brief outlines key opportunities to support a vision for ARPA-I. Based on decades of research experience at the Institute of Transportation Studies at the University of California, Berkeley, this document focuses primarily on the infrastructure that supports mobility as well as adjacent infrastructures that intersect and/or interact with transportation systems.



Approach and Research Priorities for ARPA-I

ARPA-I's mission should focus on breakthrough and enabling technologies that are critical for improving the value, sustainability, equity, and resilience of current and future transportation infrastructure. What is needed are high-risk, high-reward technologies that can revolutionize transportation infrastructure systems.

We envision that ARPA-I can:

- Prioritize and accelerate efforts that are well aligned with the long-term national goals of global climate, road safety, sustainability, equity, and resilience.
- Focus on applications that span all transportation modes and inspire new approaches to transportation mode integration that optimize resources while reducing energy and travel times.
- Leverage artificial intelligence in all aspects of transportation infrastructure construction, operations, maintenance, and reuse, including congestion reduction and safety, with safeguards around algorithmic bias.
- Broaden the concept and definition of infrastructure from materials (concrete, steel, and new zero- or negative-carbon material) to incorporate digital, organizational (human interactions), and informal (unplanned) infrastructure. Include infrastructures in energy, water, communication, and urban development that are closely related to and interdependent with transportation infrastructure.
- Use zero-carbon energy for every aspect of transportation infrastructure, including construction, operation, and maintenance.
- Encourage interdisciplinary, multi-partner teams that can address the complex socio-technical, socio-economic, and political considerations that affect and are affected by transportation in different communities and at different scales, because many complex infrastructure challenges are institutional-, policy-, community- and behavior-based.
- Foster infrastructure systems that consider equity in the face of growing environmental challenges. We need future leaders in developing inclusive solutions and evaluating their integration with complex civil infrastructure, as well as the human and natural systems in which they are embedded.
- Support high-risk, high-value investments that leverage emerging sensing, communications, and data science capabilities.
- Dramatically accelerate the transition of infrastructure research to deployment by de-risking potentially disruptive technologies that other agencies are unlikely to support and encouraging partnerships between researchers and infrastructure owners and operators who will eventually deploy the technology.

Importance of Enabling Technologies to Support Transportation Infrastructure

Over the past two decades we have seen an unprecedented convergence of technological advances that are revolutionizing communications, control, and sensing with the potential to transform our transportation infrastructure system. Efficient operation and maintenance of our transportation infrastructure requires real-time data exchange provided by information and telecommunications technology.

Enabling technologies 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—technology that lets us know what is happening on and around our highways, arterials, local streets, and bridges so that we can manage and maintain them. These technologies are also essential for improving cybersecurity, disaster detection and response, and managing climate impacts, such as sea-level rise and wildfires.

The cost to acquire and install this technology is a small percentage of the overall construction budget if installed during construction. The return on investment—measured in safety, travel time reliability, throughput, and quality of life—is less than 6 months in highly congested corridors. In addition, many transportation networks are ready to support advances in automated and connected vehicles and shared-demand management approaches.

Enabling technologies support:

- Using existing and novel data streams to understand current performance and improve our ability to anticipate future performance.
- A U.S. transportation infrastructure that is ready to support connected and automated vehicles, shared services, and electrification.
- Performance-based management to reduce congestion, make roads safer, and avoid recreating the same traffic congestion patterns that we have today with conventional vehicles.
- Infrastructure that is more thoroughly monitored throughout its lifespan, from construction and operation through maintenance and reuse, so that it may adapt to ever-changing transport demands and climate change without degrading.

Enabling technologies are now providing expanded access to the transportation infrastructure through communications and information technology. This in turn provides access metrics that can directly address underserved community needs.

Addressing Critical Infrastructure Needs

ARPA-I is a unique opportunity to realign our transportation infrastructure priorities with existing and emerging challenges, such as climate change, equity, and resilience, while continuing to provide the access and mobility benefits that underpin our economy. New ways of conceptualizing the demands for mobility are needed to encourage systems integration, holistic analysis, and innovation, including an accounting of how policy affects the demand for mobility and how individual behaviors might adapt.

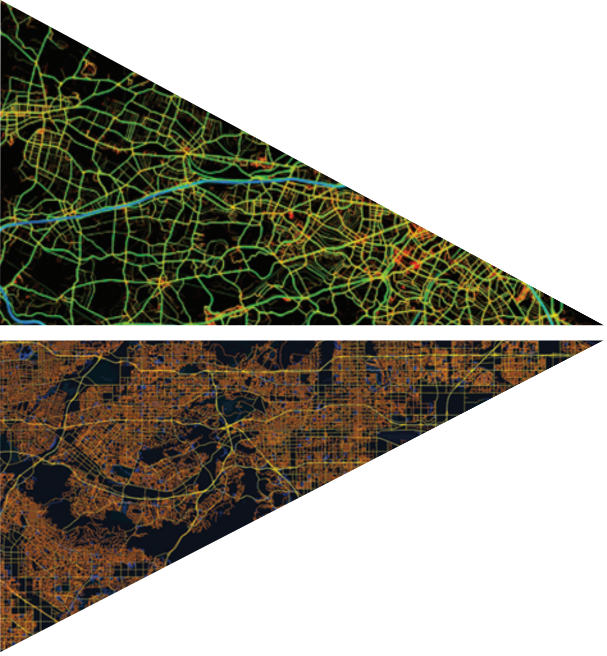
Attain carbon neutrality goals—Our transportation infrastructure systems must be designed to be efficient, generate their own energy or rely exclusively on renewable energy sources, and ultimately eliminate or capture direct emissions of greenhouse gases. In the near term, some degree of reliance on conventional means of production for basic materials, such as steel and concrete, will be necessary, but over time, production of these materials as well should be sourced from carbon-neutral production systems and processes.

Create an equitable and human-centered transportation infrastructure—The transition from our existing aging infrastructure to zero- or negative-carbon infrastructure must be equitable. Infrastructure that is equitable by design requires involving communities as partners in understanding current disparities and considering long-term solutions. The definition of infrastructure is expanding: We need to integrate organizational infrastructure (human interactions) and informal infrastructure (unplanned) to the existing physical and digital infrastructure framework. Scientific and technological advances allow us to generate and analyze data about how our infrastructure and the environment are used by communities and consider new ways that are more inclusive and equitable.

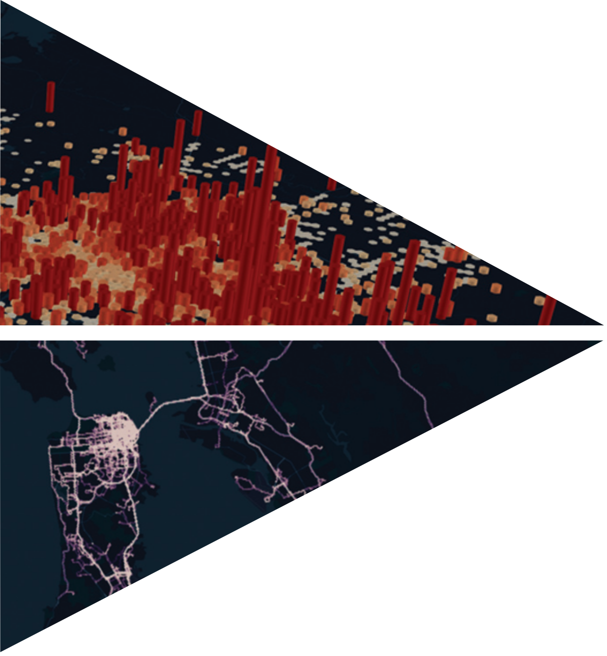
Manage the life expectancy for infrastructure—The stewardship of aging and legacy infrastructure is a great challenge we currently face. Little is known of the long-term performance of such infrastructure. Timescales in infrastructure and construction are long. Construction times alone can stretch from 2 to 10 years, and asset lifetimes in the range of 60 to 100 years or more. Over their service life, these assets face external conditions that deviate from what was anticipated at the outset, for instance, changes in population and demand, environmental conditions, or the economy. Existing infrastructure faces the need to increase load and usage—be that the number of passengers carried or the numbers of vehicles—and to remain in a state of good repair while operating at capacity. Increased usage is not the sole concern; demographic changes will alter the way we use our infrastructure. Transportation infrastructure should be more adaptive to cope with ever-changing demands. We need to significantly improve our capability in predicting and managing the life expectancy of large infrastructure.

Build resilient infrastructure—Recurring hazards over the past decade have challenged our current capacity to manage transportation infrastructure and human risks in communities across the nation. Severe wildfires increasingly impose major risks for property and human life and have grown into a key source of poor air quality. As wildfires were scorching the U.S. West Coast in 2021, hurricanes were striking the Gulf Coast states, floods were affecting the Midwest, and earlier in the year, a massive winter storm disabled the electrical grid in Texas, shutting down power and leaving millions of people without heat, water, and fuel in sub-zero temperatures.

The frequency and severity of these hazardous events are likely to increase with a changing climate, eroding the foundations of our prosperity. New materials, new structural systems, and rapid construction techniques are necessary to meet the fast-evolving needs for resilience in our communities. In the face of increased hazards, the interdependencies between resources and the built environment, including energy, water, communication, housing, emergency service centers, and transportation, must be considered. Complex multiscale, multidisciplinary modeling is essential for the design of truly resilient communities.



The following key research areas under ARPA-I can propel the U.S. transportation infrastructure to a new century.



Sensing and Autonomy for Transportation Infrastructure

Road Instrumentation for High-Performance Operations

Almost all traffic operations today can be greatly improved with expanded and updated instrumentation. For most U.S. cities, existing highway instrumentation dates back to the 1960s: loop detectors embedded in the pavement. Generally, these detectors are unreliable and often fail—a 40% failure rate is common. It is time to move to operations based on sensor systems that take advantage of communication networks with the potential to provide ubiquitous coverage and allow for future unforeseen applications to improve infrastructure systems. Although some of the sensors can be embedded in infrastructure today, the data will be useful for 10, 20, or 50 years in the future. Sensor systems to fulfill this concept ("intelligence for life") need to be either long life or adaptable for replacement.

This change requires a new monitoring architecture to support visual sensing of the road network that is enabled by artificial intelligence and computer vision or a new distributed sensing system, such as (dark) fiber-optic network, embedded in or placed along the road network. By leveraging the already existing communication network (LTE and 5G), coupled with the rapidly decreasing cost of sensors, the potential for revolutionizing traffic operations by supporting more efficient operations leads to reduced congestion costs. It also fosters better management of both anticipated and unanticipated events, such as large-scale natural disruptions (hurricanes, snowstorms, floods, heavy rains) and emergency evacuations, as well as national security. The computer vision and innovative sensor systems can also be used for structural health monitoring. With continuous monitoring of major freeways and the backbone of the transportation network, our national agencies will be better informed of threats and responses in real time.

A Resilient Cyber-Physical System for Advanced Mobility and Infrastructure Monitoring

Intelligent infrastructure enabled through the incorporation of software and sensors embedded in physical infrastructure, such as bridges, roads, railways, and vehicles, and connected to a network is central to our nation's ability to handle current and future infrastructure demands. This cyber-physical infrastructure allows analytics to be applied to a variety of current and emerging transportation infrastructures and mobility services, such as transit and shared mobility modes, route and traffic management, autonomous and semi-autonomous cars and trucks, and fleet management. The development of a scalable, resilient, and learning digital transportation infrastructure requires a multidisciplinary approach that combines the best of information and communication technology with cybersecurity and high-confidence design attributes. High-confidence design is the ability to build systems that are fault tolerant and resistant to cyberattacks.

Two critical aspects of a cyber-physical infrastructure include enabling broadband and creating infrastructure monitoring applications.

Enabling broadband wired and wireless networks

High-speed wireline and wireless broadband are at the heart of a cyber-physical infrastructure system. Investments in broadband infrastructure supports cross-sector research to validate intelligent infrastructure strategies, tools, models, and data collection and sharing processes. Scalable and secure networks support high reliability and guaranteed millisecond latencies that are critical for contemporary automatic control systems. Improving wired and wireless communications simplifies the deployment of intelligence into transportation applications. For example, low-latency wireless networks can dramatically reduce the weight of aerial and land vehicles and their interaction with the transportation infrastructure. They also enable operation of complex, data-intensive systems, including the monitoring of conditions in a real-time system without lags.

From the vehicular perspective, these cyber-physical systems enable communication and control between vehicles in platoons, as well as other devices, such as aerial vehicles, with communication delays between the stimulus and the response in the order of milliseconds.

From the infrastructure perspective, a cyber-physical system uses information and communications technology 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 efficiency gains, reduce deleterious environmental effects, and promote economic growth and the safety and well-being of communities.

Supporting the ability to monitor transportation infrastructure

State departments of transportation need support and guidance to be fully equipped to manage and make efficient use of emerging sensor networks. States could greatly benefit from strong guidance on the design and features of infrastructure monitoring applications, including an understanding of the assets and services that deserve priority monitoring, the implementation plans for deploying this new layer of infrastructure, and the data-centered strategies needed to manage, store, analyze, and extract value from these monitoring networks.

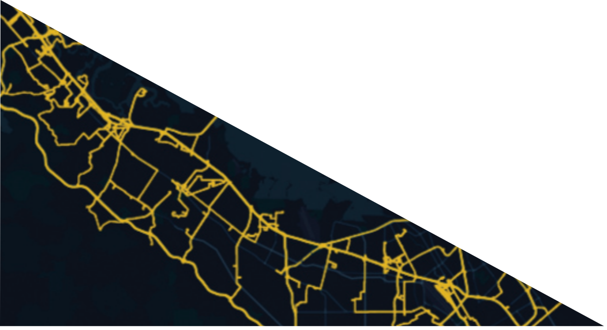
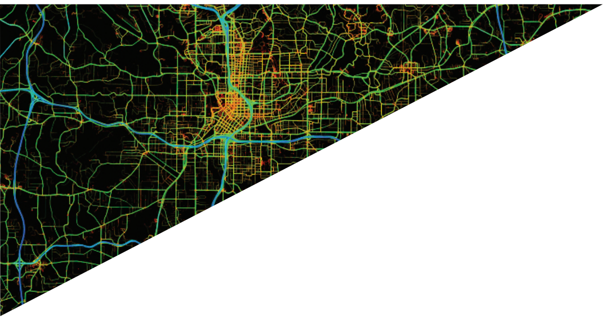
Synergies Between Road Infrastructure and Vehicle Automation

Developers of automated vehicles have been reluctant to acknowledge their interdependence with infrastructure, partly because of concerns about funding and timely delivery of needed infrastructure enhancements. Yet, opportunities for vehicle automation to improve the safety, efficiency, and traffic flow of the road network (and to deliver those improvements sooner) are greatly enhanced if the vehicles and the public infrastructure can operate as a well-integrated system. One promising approach is the fusing of vehicular data to complement, and sometimes replace, road infrastructure instrumentation. The implementation and use of vehicle-borne sensing devices and networks associated with vehicular automation has the potential to significantly reduce the need for costly infrastructure-based instrumentation.

Another promising approach is to consider infrastructure instrumentation that dramatically improves the performance of automated vehicles. For example, low-cost electronic and road-marking changes can be applied throughout the road network by developing a consistent framework for machine-readable characterization of roadway infrastructure that can be understood by automated driving systems that need to operate on that infrastructure. Applying the road markings involves developing a nationwide roadway infrastructure database to track and manage the real-time maintenance status on precise locations of road works and incidents. With a roadway reference marking (delineation) technology that does not depend on visible light reflections off the pavement, automated driving systems could leverage this system in all weather and lighting conditions. Currently, automated driving systems must acquire and maintain this mapping data themselves, which may lack accuracy and consistency.

Autonomy in Construction, Operations, and Maintenance

Robotics, sensing, and data analytics can create significant efficiencies that will revolutionize the way we design, construct, maintain, and operate infrastructure. Autonomous infrastructure senses and responds to changing conditions. At the same time, the boundary between design, construction, and operation is blurring, necessitating new approaches and synergies to management, materials innovation, and engineering. Autonomy enables insights into how the built environment is functioning that were previously unattainable and empowers new models that leverage data to achieve efficiencies. In operations, autonomy can bring short- and long-term efficiencies. For example, mixed autonomy, with some autonomous vehicles and others human driven, is likely to provide short-term improvements around traffic flow, safety, and emissions.

Considering Infrastructure in the Context of Societal Challenges

A Carbon-Neutral Transportation Infrastructure

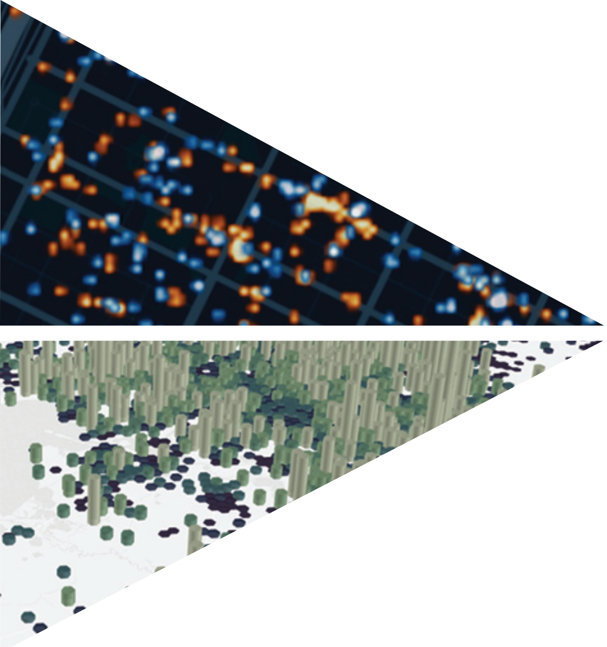
Although vehicular electrification and low-carbon fuels are a step forward in decarbonizing the transportation sector, these approaches are likely to be insufficient, especially given increases in vehicle miles traveled. From the perspective of transportation infrastructure, a primary challenge is to reduce the greenhouse gas emissions associated with the construction and reconstruction, maintenance, rehabilitation, and end-of-life phases. There is considerable room for reducing infrastructure-related greenhouse gas emissions because current materials and construction practices are not engineered to achieve this goal. This approach requires research on improved materials and techniques as well as changes to public infrastructure policies, specifications, designs, and procurement processes to make them compatible with the emerging materials and techniques. As the existing transportation infrastructure ages, recyclability becomes a cornerstone of achieving carbon neutrality, reducing depletion of nonrenewable natural resources, and promoting a circular economy by diverting end-of-life infrastructure residues from landfills and feeding them into a new market. Additional key efforts include providing the support infrastructure needed for vehicle electrification, including the development of widespread electric vehicle charging infrastructure and associated grid upgrades, as well as hydrogen fuel production, delivery, and dispensing systems.

A Safe Transportation System for All Users

Despite technological improvements around human factors and collision avoidance, road safety remains a critical area of concern. Safety is not only a moral imperative but also an economic one. In 2020, U.S. road collisions claimed the lives of 38,680 people. Of those victims, most were occupants or drivers of a motor vehicle, but an increasing percentage were pedestrians, motorcyclists, and bicyclists. The estimated economic cost of all motor vehicle traffic crashes in the United States exceeds $250 billion.

A safe infrastructure is critical to improving our road safety performance. Concerns around road safety have resulted in innovative policy initiatives promoting a system in which no road user can be severely or fatally injured—a goal consistent with Vision Zero. Opportunities to innovate around road safety have been recognized at the federal level and are included in the National Road Safety Strategy, which calls for a Safe Systems approach.

A safe infrastructure depends mostly on three elements: safer vehicles, safer road infrastructure, and safer speeds. To improve safety, we need vehicular technologies that more proactively address road safety, infrastructure designs that reflect and promote a safe systems approach, and speed limits that account for all modes of travel and types of users. Building a national data safety system of near-misses that includes an estimate of the kinetic energy carried by all users can also help prioritize safety, especially for the most vulnerable.



Developing Infrastructure Planning Tools and Processes

Efficient Metropolitan-Scale Modeling

Simulations of large transportation networks containing millions of nodes, links, and vehicles are key to developing novel congestion control approaches, for assessing the resilience of the transportation system, developing alternative plans in quasi-real time, and evaluating emerging policies and technologies. The digital platforms necessary for these large-scale simulations rely on high-performance computing capabilities and can generate results within minutes. This provides significantly improved support for practitioners making operational and investment decisions for both short- and long-term planning horizons.

Current efforts focus on building regional digital twins that are driven by real-world sensor data. The challenge with developing digital twins in transportation is to capture the very complex road network dynamics in a learned model while still maintaining computational speeds. High-performance computing provides the ability to generate massive data sets through iterative simulations. Using deep learning, these data sets can generate surrogate models that can be delivered directly to practitioners for evaluating and predicting the impacts of their infrastructure improvement projects and policies. By generating performance metrics that cover not only travel times but also congestion metrics, practitioners can then readily assess the community experience, for example, changes in traffic profiles near schools or emissions in communities of concern. Cities will have advanced decision-support tools to predict, track, and adjust to their communities' needs.

Simulations should use large-scale location data in travel demand modeling, corridor and freight planning, and disaster and emergency management. For example, changes in the transportation network can be analyzed and mapped for any given area, city, or roadway facility over large time frames. This can provide a deeper understanding of the complex interactions and dynamics of transportation networks. Such data has the potential to provide highly valuable insights for both near-term operations and long-term planning of next-generation transportation systems and transportation policy planning.

Improved Transportation Infrastructure Planning and Delivery

There is misplaced optimism that large infrastructure projects can be delivered quickly, on time, on budget, and with minimal environmental impact. Projects typically take longer than expected, and construction costs are higher than anticipated. Considering avenues for improving project planning, especially for projects that are climate friendly, is critical to the success of a major national infrastructure initiative. Key ideas include:

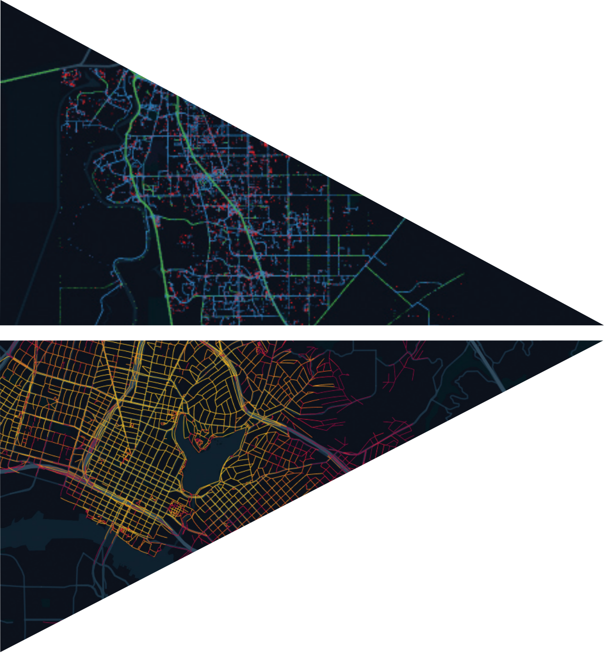
- Improve cost estimations by comparing projects under consideration to similar projects, particularly for their cost and delivery timelines, and including sufficient contingency estimates. Governments and researchers in the United Kingdom, European Union, Australia, and the Asia-Pacific use a method called "reference class forecasting." Augment this analysis with detailed comparisons of transaction costs, such as financing, legal, right-of-way, and environmental processes.
- Identify policy options for centralizing infrastructure delivery and financing. In tandem, the federal government can evaluate additional steps to improve the use of risk analysis, independent external oversight, and peer review of projects across transportation infrastructure project types.
- Develop the simultaneous and combined use of environmental and cost life-cycle and cost assessment models in decision-making. In parallel, develop decision-support tools for incorporating such assessments.
- Establish a clearinghouse with detailed information that allows for rigorous comparative analysis of individual project costs, risk management, life-cycle assessments, peer review processes, equity impacts, and project delivery methods of forthcoming projects.
- Condition federal funding for local transportation infrastructure projects on meeting certain performance benchmarks, such as reduced vehicle miles traveled, greenhouse gas emissions, and cost per rider or user.

Whole-Life Transportation Infrastructure Engineering and Decision-Support Tools

ISO 55000 standards on asset management highlight the importance of whole-life management of physical infrastructure and emphasize realizing value rather than minimizing cost. A whole-life digital twin framework can potentially support infrastructure owners to secure the best value for money throughout an infrastructure's lifetime and to make value-based infrastructure management decisions. However, data requirements for short- and long-term management of infrastructure need to be identified before a new generation of a whole-life digital twin framework is developed. Information required includes data quality and its degradation with time, survival rates of hardware and software components, and the associated error propagation and costing of management and maintenance.

Policy and Infrastructure Innovations for Emerging Travel Modes

Infrastructure and policy considerations often lag the surging interest in novel travel modes and service innovations. For example, ridehailing and standing electric scooter sharing services went through a turbulent decade of policy recognition and adaptation. In a similar way, emerging modes, such as air uncrewed and crewed autonomous aerial vehicles for civilian applications, will face similar challenges. Concerns about who benefits from these systems and who bears the costs of their funding and operation remain at the forefront of policy-makers. Similarly, public actions taken to plan for these systems will have ripple effects on the feasibility and impacts of novel modes. For example, drones are envisioned to fly in the low-altitude space of about 200 to 500 feet. As a result, the allocation of this airspace resource must consider safety, privacy, efficiency, and ease of human participation. Systems analysis that builds on the concept of air corridors provides a scalable and intuitive way for managing the airspace for use by a large number of low-flying aerial vehicles. These corridors can be updated in real time according to changes in the airspace. Trunks and branches of air highways, similar to ground-based highway systems, as well as first- and last-mile considerations, will require significant operational and policy design decisions.



About the Institute of Transportation Studies

For 75 years, the Institute of Transportation Studies at the University of California, Berkeley (its.berkeley.edu), 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 per year. More than 150 faculty members and staff researchers and more than 100 graduate students from multiple disciplines and backgrounds come together into specialized centers organized within the Institute.

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