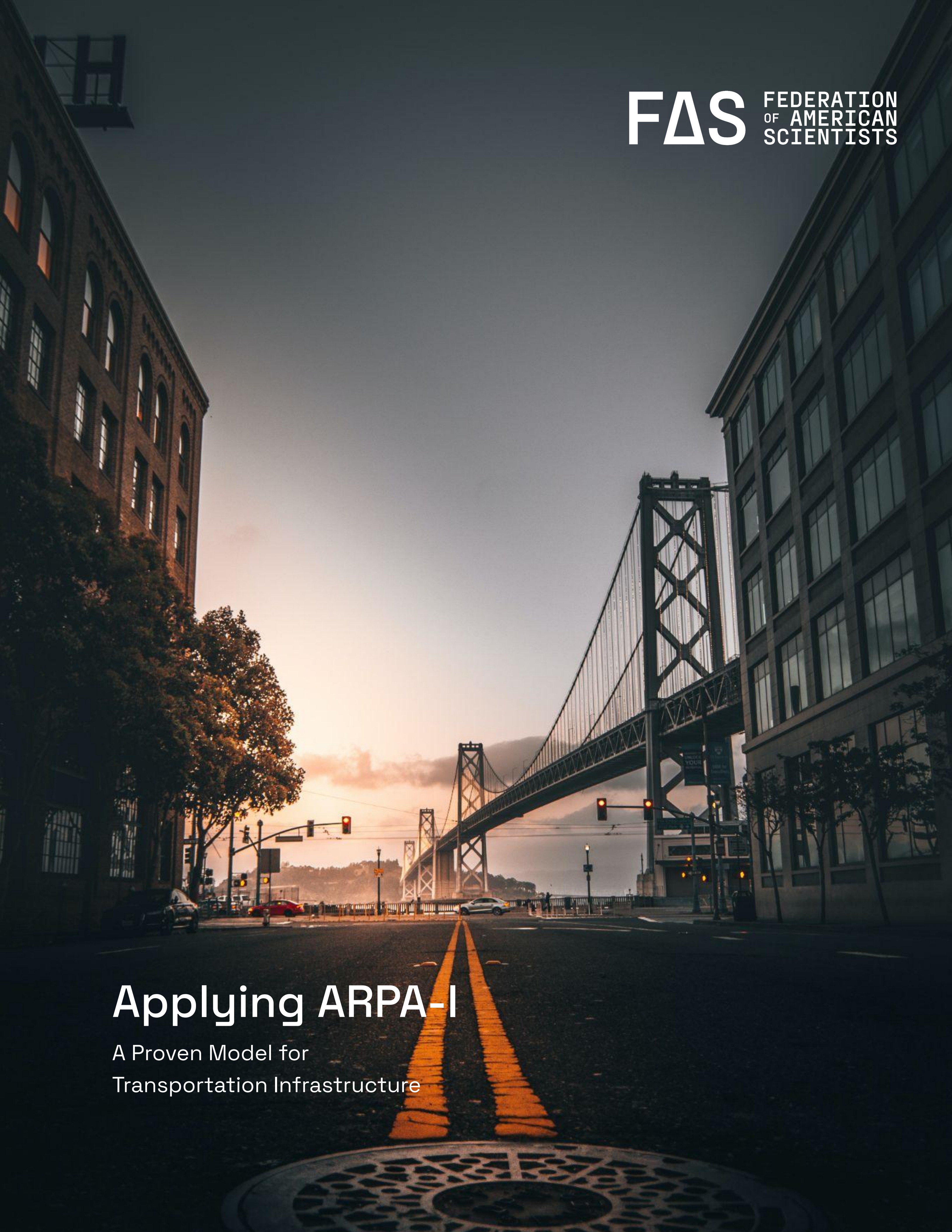


FAS FEDERATION OF AMERICAN SCIENTISTS

Applying ARPA-I

A Proven Model for
Transportation Infrastructure

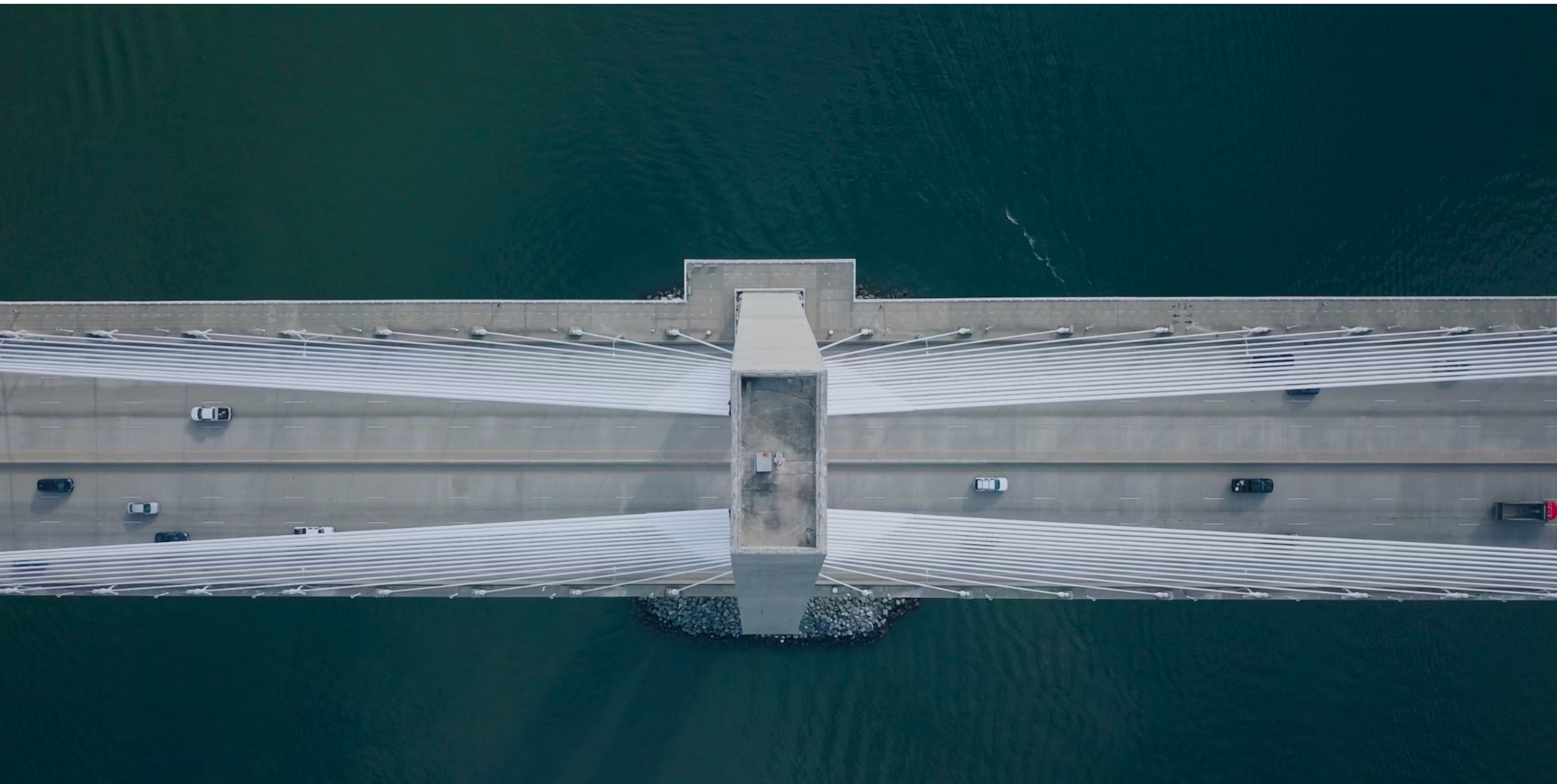
About the Federation of American Scientists

After the devastating bombings of Hiroshima and Nagasaki, a group of atomic researchers, deeply concerned about the use of science for malice, created an organization committed to using science and technology to benefit humanity. The group they created – the Federation of Atomic Scientists – soon became the Federation of American Scientists (FAS) in recognition of the hundreds of scientists across diverse disciplines who joined together to advance science policy and counter scientific misinformation.

Over 75 years later, the FAS is still working to minimize the risks of significant global threats, arising from nuclear weapons, biological and chemical agents, and climate change. The organization also works to advance progress on a broad suite of contemporary issues where science, technology, and innovation policy can deliver dramatic progress, and seeks to ensure that scientific and technical expertise have a seat at the policymaking table.

About this Report

The U.S. Department of Transportation's (USDOT) Office of the Assistant Secretary for Research and Technology has engaged the FAS to support expert outreach to scope research and technology topics suitable for their advanced research portfolio, given recent authorizations and appropriations for new programs like the Advanced Research Projects Agency-Infrastructure (ARPA-I). This scoping has been done through workshops aimed at surfacing advanced research program concepts. This report is a result of many of the insights gathered by the FAS from these workshops and outreach within the transportation infrastructure innovation ecosystem.



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Executive Summary

In November 2021, Congress passed the Infrastructure Investment and Jobs Act (IIJA), which included $550 billion in new funding for dozens of new programs across the U.S. Department of Transportation (USDOT). Alongside historic investments in America's roads and bridges, the bill created the Advanced Research Projects Agency-Infrastructure (ARPA-I). Building on successful models like the Defense Advanced Research Projects Agency (DARPA) and the Advanced Research Program-Energy (ARPA-E), ARPA-I's mission is to bring the nation's most innovative technology solutions to bear on our most significant transportation infrastructure challenges.

ARPA-I must navigate America's uniquely complex infrastructure landscape, characterized by limited federal research and development funding compared to other sectors, public sector ownership and stewardship, and highly fragmented and often overlapping ownership structures that include cities, counties, states, federal agencies, the private sector, and quasi-public agencies. Moreover, the new agency needs to integrate the strong culture, structures, and rigorous ideation process that ARPAs across government have honed since the 1950s. This report is a primer on how ARPA-I, and its stakeholders, can leverage this unique opportunity to drive real, sustainable, and lasting change in America's transportation infrastructure.

How to Use This Report

This report highlights the opportunity ARPA-I presents; orients those unfamiliar with the transportation infrastructure sector to the unique challenges it faces; provides a foundational understanding of the ARPA model and its early-stage program design; and empowers experts and stakeholders to get involved in program ideation. However, individual sections can be used as standalone tools depending on the reader's prior knowledge of and intended involvement with ARPA-I.

* If you are unfamiliar with the background, authorization, and mission of ARPA-I, refer to the section "An Opportunity for Transportation Infrastructure Innovation."
* If you are relatively new to the transportation infrastructure sector, refer to the section "Unique Challenges of the Transportation Infrastructure Landscape."
* If you have prior transportation infrastructure experience or expertise but are new to the ARPA model, you can move directly to the sections beginning with "Core Tenets of ARPA Success."

An Opportunity for Transportation Infrastructure Innovation

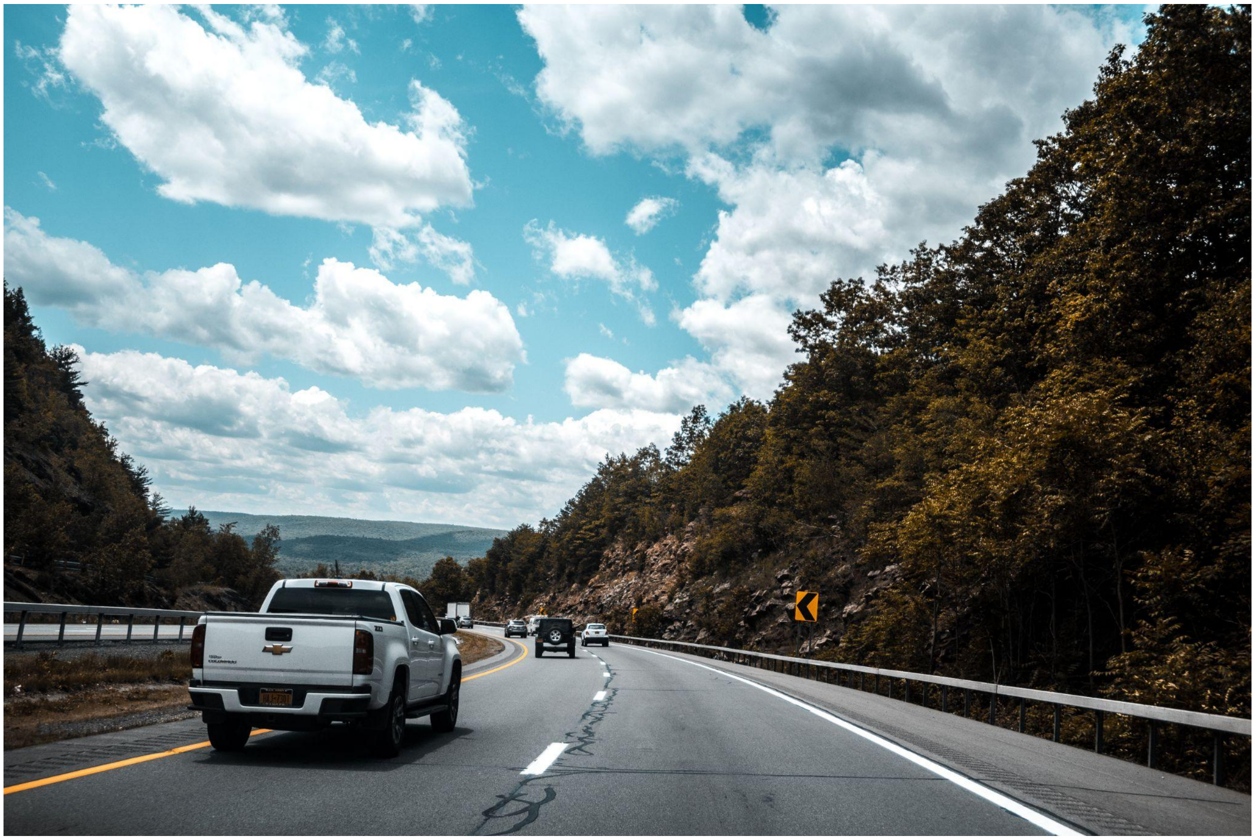
In November 2021, Congress passed the Infrastructure Investment and Jobs Act (IIJA) authorizing the U.S. Department of Transportation (USDOT) to create the Advanced Research Projects Agency-Infrastructure (ARPA-I), among other new programs. ARPA-I's mission is to advance U.S. transportation infrastructure by developing innovative science and technology solutions that:

- lower the long-term cost of infrastructure development, including costs of planning, construction, and maintenance;
- reduce the life cycle impacts of transportation infrastructure on the environment, including through the reduction of greenhouse gas emissions;
- contribute significantly to improving the safe, secure, and efficient movement of goods and people; and
- promote the resilience of infrastructure from physical and cyber threats.

ARPA-I will achieve this goal by supporting research projects that:

- advance novel, early-stage research with practicable application to transportation infrastructure;
- translate techniques, processes, and technologies, from the conceptual phase to prototype, testing, or demonstration;
- develop advanced manufacturing processes and technologies for the domestic manufacturing of novel transportation-related technologies; and
- accelerate transformational technological advances in areas in which industry entities are unlikely to carry out projects due to technical and financial uncertainty.

ARPA-I is the newest addition to a long line of successful ARPAs that continue to deliver breakthrough innovations across the defense, intelligence, energy, and health sectors. The U.S. Department of Defense established the pioneering Defense Advanced Research Projects Agency (DARPA) in 1958 in response to the Soviet launch of the Sputnik satellite to develop and demonstrate high-risk, high-reward technologies and capabilities to ensure U.S. military technological superiority and confront national security challenges. Throughout the years, DARPA programs have been responsible for significant technological advances with implications beyond defense and national security, such as the early stages of the internet, the creation of the global positioning system (GPS), and the development of mRNA vaccines critical to combating COVID-19.



In light of the many successful advancements seeded through DARPA programs, the government replicated the ARPA model for other critical sectors, resulting in the Intelligence Advanced Research Projects Activity (IARPA) within the Office of the Director of National Intelligence, the Advanced Research Projects Agency-Energy within the Department of Energy, and, most recently, the Advanced Research Projects Agency-Health (ARPA-H) within the Department of Health and Human Services.

Now, there is the opportunity to bring that same spirit of untethered innovation to solve the most pressing transportation infrastructure challenges of our time. The United States has long faced a variety of transportation infrastructure-related challenges, due in part to low levels of federal research and development (R&D) spending in this area; the fragmentation of roles across federal, state, and local government; risk-averse procurement practices; and sluggish commercial markets. These challenges include:

- **Roadway safety**
  According to the National Highway Traffic Safety Administration, an estimated 42,915 people died in motor vehicle crashes in 2021, up 10.5% from 2020.

* **Transportation emissions**
  According to the U.S. Environmental Protection Agency, the transportation sector accounted for 27% of U.S. greenhouse gas (GHG) emissions in 2020, more than any other sector.

* **Aging infrastructure and maintenance**
  According to the 2021 Report Card for America's Infrastructure produced by the American Society of Civil Engineers, 42% of the nation's bridges are at least 50 years old and 7.5% are "structurally deficient."

The Fiscal Year 2023 Omnibus Appropriations Bill awarded ARPA-I its initial appropriation in early 2023. Yet even before that, the Biden-Harris Administration saw the potential for ARPA-I-driven innovations to help meet its goal of net-zero GHG emissions by 2050, as articulated in its Net-Zero Game Changers Initiative. In particular, the Administration identified smart mobility, clean and efficient transportation systems, next-generation infrastructure construction, advanced electricity infrastructure, and clean fuel infrastructure as "net-zero game changers" that ARPA-I could play an outsize role in helping develop.

For ARPA-I programs to reach their full potential, agency stakeholders and partners need to understand not only how to effectively apply the ARPA model but how the unique circumstances and challenges within transportation infrastructure need to be considered in program design.

Unique Challenges of the Transportation Infrastructure Landscape

Using ARPA-I to advance transportation infrastructure breakthroughs requires an awareness of the most persistent challenges to prioritize and the unique set of circumstances within the sector that can hinder progress if ignored. Below are summaries of key challenges and considerations for ARPA-I to account for, followed by a deeper analysis of each challenge.

* Federal R&D spending on transportation infrastructure is considerably lower than other sectors, such as defense, healthcare, and energy, as evidenced by federal spending as a percentage of that sector's contribution to gross domestic product (GDP).

* The transportation sector sees significant private R&D investment in vehicle and aircraft equipment but minimal investment in transportation infrastructure because the benefits from those investments are largely public rather than private.

* Market fragmentation within the transportation system is a persistent obstacle to progress, resulting in reliance on commercially available technologies and transportation agencies playing a more passive role in innovative technology development.
* The fragmented market and multimodal nature of the sector pose challenges for allocating R&D investments and identifying customers.

Lower Federal R&D Spending in Transportation Infrastructure

Federal R&D expenditures in transportation infrastructure lag behind those in other sectors. This gap is particularly acute because, unlike for some other sectors, federal transportation R&D expenditures often fund studies and systems used to make regulatory decisions rather than technological innovation. The table below compares actual federal R&D spending and sector expenditures for 2019 across defense, healthcare, energy, and transportation as a percentage of each sector's GDP. The federal government spends orders of magnitude less on transportation than other sectors: energy R&D spending as a percentage of sector GDP is nearly 15 times higher than transportation, while health is 13 times higher and defense is nearly 38 times higher.

Agency[1]	Actual federal R&D spending, 2019	Value added by industry and % of U.S. GDP, 2019	2019 federal R&D spending as % of sector GDP
Defense	$54.69 billion	$732 billion (3.4%)	7.5%
Health and Human Services	$38.51 billion	$1,452 billion (6.8%)[2]	2.7%
Energy	$18.27 billion	$607 billion (2.8%)[3]	3.0%
Transportation	$1.10 billion	$610 billion (2.9%)[4]	0.2%

Public Sector Dominance Limits Innovation Investment

Since 1990, total investment in U.S. R&D has increased by roughly 9 times. When looking at the source of R&D investment over the same period, the private and public sectors invested approximately the same amount of R&D funding in 1982, but today the rate of R&D investment is nearly 4 times greater for the private industry than the government.

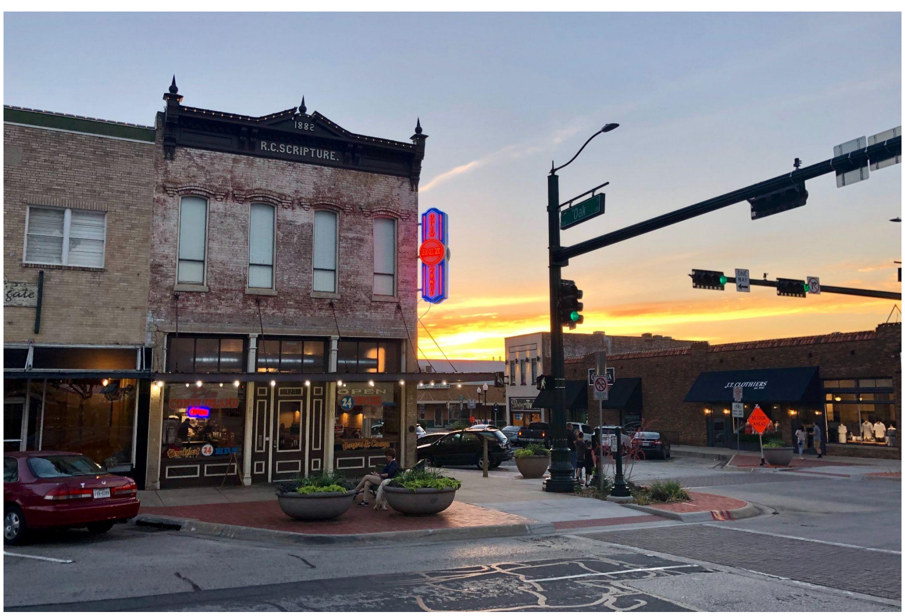
[1] The comparison of federal R&D spending and sector expenditures for 2019 is similar to those for the years 2020 and 2021.
[2] Excludes GDP value-adds relating to Social Assistance
[3] Includes GDP value-adds relating to oil and gas extraction, utilities, and petroleum and coal products
[4] Excludes GDP value adds relating to Warehousing

While there are problems with the bulk of R&D coming from the private sector, such as innovations to promote long-term public goods being overlooked because of more lucrative market incentives, industries that receive considerable private R&D funding still see significant innovation breakthroughs. For example, the medical industry saw $161.8 billion in private R&D funding in 2020 compared to only $61.5 billion from federal funding. More than 75% of this private industry R&D occurred within the biopharmaceutical sector where corporations have profit incentives to be at the cutting edge of advancements in medicine.

The transportation sector has one robust domain for private R&D investment: vehicle and aircraft equipment manufacturing. In 2018, total private R&D was [$52.6 billion](). Private sector transportation R&D focuses on individual customers and end users, creating better vehicles, products, and efficiencies. The vast majority of that private sector R&D does not go toward infrastructure because the benefits are largely public rather than private. Put another way, the United States invests more than 50 times the amount of R&D into vehicles than the infrastructure systems upon which those vehicles operate.

Market Fragmentation across Levels of Government

Despite opportunities within the public-dominated transportation infrastructure system, market fragmentation is a persistent obstacle to rapid progress. Each level of government has different actors with different objectives and responsibilities. For instance, at the federal level, USDOT provides national-level guidance, policy, and funding for transportation across aviation, highway, rail, transit, ports, and maritime modes. Meanwhile, the states set goals, develop transportation plans and projects, and manage transportation networks like the interstate highway system. Metropolitan planning organizations take on some of the planning functions at the regional level, and local governments often maintain much of their infrastructure. There are also local individual agencies that operate facilities like airports, ports, or tollways organized at the state, regional, or local level. Programs that can use partnerships to cut across this tapestry of systems are essential to driving impact at scale.



Local agencies have limited access and capabilities to develop cross-sector technologies. They have access to limited pools of USDOT funding to pilot technologies and thus generally rely on commercially available technologies to increase the likelihood of pilot success. One shortcoming of this current process is that both USDOT and infrastructure owner-operators (IOOs) play a more passive role in developing innovative technologies, instead depending on merely deploying market-ready technologies.

Multiple Modes, Customers, and Jurisdictions Create Difficulties in Efficiently Allocating R&D Resources

The transportation infrastructure sector is a multimodal environment split across many modes, including aviation, maritime, pipelines, railroads, roadways (which includes biking and walking), and transit. Each mode includes various customers and stakeholders to be considered. In addition, in the fragmented market landscape federal, state, and local departments of transportation have different—and sometimes competing—priorities and mandates. This dynamic creates difficulties in allocating R&D resources and considering access to innovation across these different modes.

Customer identification is not "one size fits all" across existing ARPAs. For example, DARPA has a laser focus on delivering efficient innovations for one customer: the Department of Defense. For ARPA-E, it is less clear; their customers range from utility companies to homeowners looking to benefit from lower energy costs. ARPA-I would occupy a space in between these two cases, understanding that its end users are IOOs—entities responsible for deploying infrastructure in many cases at the local or regional level.

However, even with this more direct understanding of its customers, a shortcoming of a system focused on multiple modes is that transportation infrastructure is very broad, occupying everything from self-healing concrete to intersection safety to the deployment of electrified mobility and more. Further complicating matters is the rapid evolution of technologies and expectations across all modes, along with the rollout of entirely new modes of transportation. These developments raise questions about where new technologies and capabilities fit in existing modal frameworks, what actors in the transportation infrastructure market should lead their development, and who the ultimate "customers" or end users of innovation are.

Having a matrixed understanding of the rapid technological evolution across transportation modes and their potential customers is critical to investing in and building infrastructure for the future, given that transportation infrastructure investments not only alter a region's movement of people and goods but also fundamentally impact its development. ARPA-I is poised to shape learnings across and in partnership with USDOT's modes and various offices to ensure the development and refinement of underlying technologies and approaches that serve the needs of the entire transportation system and users across all modes.

Core Tenets of ARPA Success

Success using the ARPA model comes from demonstrating new innovative capabilities, building a community of people (an "ecosystem") to carry the progress forward, and having the support of key decision-makers. Yet the ARPA model can only be successful if its program directors (PDs), fellows, stakeholders, and other partners understand the unique structure and inherent flexibility required when working to create a culture conducive to spurring breakthrough innovations. From a structural and cultural standpoint, the ARPA model is unlike any other agency model within the federal government, including all existing R&D agencies. Partners and other stakeholders should embrace the unique characteristics of an ARPA.

Cultural Components

ARPAs should take risks.

An ARPA portfolio may be the closest thing to a venture capital portfolio in the federal government. They have a mandate to take big swings so should not be limited to projects that seem like safe bets. ARPAs will take on many projects throughout their existence, so they should balance quick wins with longer-term bets while embracing failure as a natural part of the process.

ARPAs should constantly evaluate and pivot when necessary.

An ARPA needs to be ruthless in its decision-making process because it has the ability to maneuver and shift without the restriction of initial plans or roadmaps. For example, projects around more nascent technology may require more patience, but if assessments indicate they are not achieving intended outcomes or milestones, PDs should not be afraid to terminate those projects and focus on other new ideas.

ARPAs should stay above the political fray.

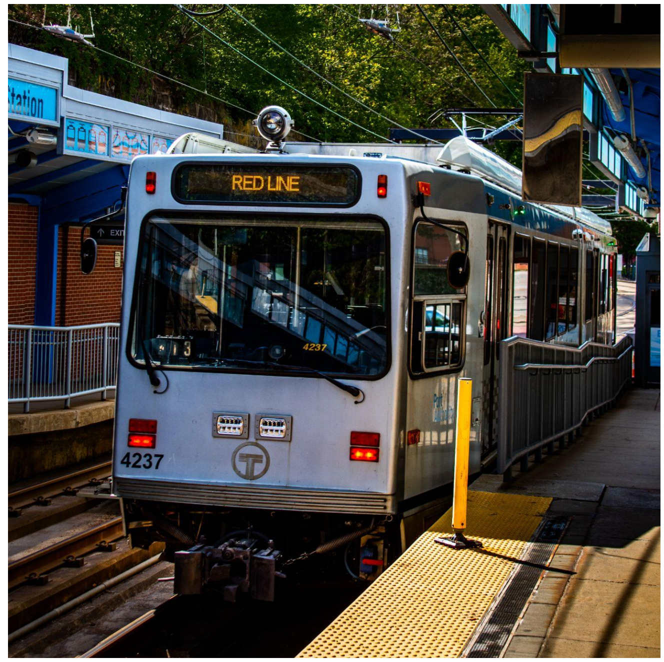
ARPAs can consider new and nontraditional ways to fund innovation, and thus should not be caught up in trends within their broader agency. As different administrations onboard, new offices get built and partisan priorities may shift, but ARPAs should limit external influence on their day-to-day operations.

ARPA team members should embrace an entrepreneurial mindset.

PDs, partners, and other team members need to embrace the creative freedom required for success and operate much like entrepreneurs for their programs. Valued traits include a propensity toward action, flexibility, visionary leadership, self-motivation, and tenacity.

ARPA team members must move quickly and nimbly.

Trying to plan out the agency's path for the next two years, five years, 10 years, or beyond is a futile effort and can be detrimental to progress. ARPAs require ultimate flexibility from day to day and year to year. Compared to other federal initiatives, ARPAs are far less bureaucratic by design, and forcing unnecessary planning and bureaucracy on the agency will slow progress.



Collegiality must be woven into the agency's fabric.

With the rapidly shifting and entrepreneurial nature of ARPA work, the federal staff, contractors, and other agency partners need to rely on one another for support and assistance to seize opportunities and continue progressing as programs mature and shift.

Outcomes matter more than following a process.

ARPA PDs must be free to explore potential program and project ideas without any predetermination. The agency should support them in pursuing big and unconventional ideas unrestricted by a particular process. While there is a process to turn their most unconventional and groundbreaking ideas into funded and functional projects, transformational ideas are more important than the process itself during idea generation.

ARPA team members welcome feedback.

Things move quickly in an ARPA, and decisions must match that pace, so individuals such as fellows and PDs must work together to offer as much feedback as possible. Constructive pushback helps avoid blind alleys and thus makes programs stronger.

Structural Components

The ARPA Director sets the vision.

The Director's vision helps attract the right talent and appropriate levels of ambition and focus areas while garnering support from key decision-makers and luminaries. This vision will dictate the types and qualities of PDs an ARPA will attract to execute within that vision.

PDs can make or break an ARPA and set the technical direction.

Because the power of the agency lies within its people, ARPAs are typically flat organizations. An ARPA should seek to hire the best and most visionary thinkers and builders as PDs, enable them to determine and design good programs, and execute with limited hierarchical disruption. During this process, PDs should engage with decision-makers in the early stages of the program design to understand the needs and realities of implementers.

Contracting helps achieve goals.

The ARPA model allows PDs to connect with universities, companies, nonprofits, organizations, and other areas of government to contract necessary R&D. This allows the program to build relationships with individuals without needing to hire or provide facilities or research laboratories.

Interactions improve outcomes.

From past versions of ARPA that attempted remote and hybrid environments, it became evident that having organic collisions across an ARPA's various roles and programs is important to achieving better outcomes. For example, ongoing in-person interactions between and among PDs and technical advisors are critical to idea generation and technical project and program management.

Staff transitions must be well facilitated to retain institutional knowledge.

One of ARPA's most unique structural characteristics is its frequent turnover. PDs and fellows are term-limited, and ARPAs are designed to turn over those key positions every few years as markets and industries evolve, so having thoughtful transition processes in place is vital, including considering the role of systems engineering and technical assistance (SETA) contractors in filling knowledge gaps, cultivating an active alumni network, and staggered hiring cycles so that large numbers of PDs and fellows are not all exiting their service at once.

Scaling should be built into the structure.

It cannot be assumed that if a project is successful, the private sector will pick that technology up and help it scale. Instead, an ARPA should create its own bridge to scaling in the form of programs dedicated to funding projects proven in a test environment to scale their technology for real-world application.

Technology-to-market advisors play a pivotal role.

Similarly to the dedicated funding for scaling described above, technology-to-market advisors are responsible for thinking about how projects make it to the real world. They should work hand in hand with PDs even in the early stages of program development to provide perspectives on how projects might commercialize and become market-ready. Without this focus, technologies run the risk of dying on the vine—succeeding technically, but failing commercially.

A Primer on ARPA Ideation

Tackling grand challenges in transportation infrastructure through ARPA-I requires understanding what is unique about its program design. This process begins with considering the problem worth solving, the opportunity that makes it a ripe problem to solve, a high-level idea of an ARPA program's fit in solving it, and a visualization of the future once this problem has been solved. This process of early-stage program ideation requires a shift in one's thinking to find ideas for innovative programs that fit the ARPA model in terms of appropriate ambition level and suitability for ARPA structure and objectives. It is also an inherently iterative process, so while creating a "wireframe" outlining the problem, opportunity, program objectives, and future vision may seem straightforward, it can take months of refining.

Common Challenges

No clear diagnosis of the problem

Many challenges facing our transportation infrastructure system are not defined by a single problem; rather, they are a conglomeration of issues that simultaneously need addressing. An effective program will not only isolate a single problem to tackle, but it will approach it at a level where something can be done to solve it through root cause analysis.

Thinking small and narrow

On the other hand, problems being considered for ARPA programs can be isolated down to the point that solving them will not drive transformational change. In this situation, narrow problems would not cater to a series of progressive and complementary projects that would fit an ARPA.

Incorrect framing of opportunities:

When doing early-stage program design, opportunities are sometimes framed as "an opportunity to tackle a problem." Rather, an opportunity should reflect a promising method, technology, or approach already in existence but which would benefit from funding and resources through an advanced research agency program.

Approaching solutions solely from a regulatory or policy angle

While regulations and policy changes are a necessary and important component of tackling challenges in transportation infrastructure, approaching issues through this lens is not the mandate of an ARPA. ARPAs focus on supporting breakthrough innovations in developing new methods, technologies, capabilities, and approaches. Additionally, regulatory approaches to problem-solving can often be subject to lengthy policy processes.

No explicit ARPA role

An ARPA should pursue opportunities to solve problems where, without its intervention, breakthroughs may not happen within a reasonable timeframe. If the public or private sector already has significant interest in solving a problem, and they are well on their way to developing a transformational solution in a few years or less, then ARPA funding and support might provide a higher value-add elsewhere.

Lack of throughline

The problems identified for ARPA program consideration should be present as themes throughout the opportunities chosen to solve them as well as how programs are ultimately structured. Otherwise, a program may lack a targeted approach to solving a particular challenge.

Forgetting about end users

Human-centered design should be at the heart of how ARPA programs are scoped, especially when considering the scale at which designers need to think about how solving a problem will provide transformational change for everyday users.

Being solutions-oriented

Research programs should not be built with predetermined solutions in mind; they should be oriented around a specific problem to ensure that any solutions put forward are targeted and effective.

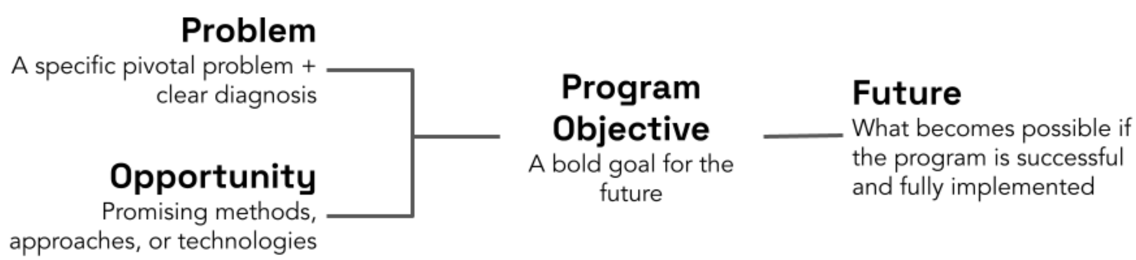
Not being realistic about direct outcomes of the program

Program objectives should not simply restate the opportunity, nor should they jump to where the world will be many years after the program has run its course. They should separate the tactical elements of a program and what impact they will ultimately drive. Designers should consider their program as one key step in a long arc of commercialization and adoption, with a firm sense of who needs to act and what needs to happen to make a program objective a reality.

Keeping these common mistakes in mind throughout the design process ensures that programs are properly scoped, appropriately ambitious, and in line with the agency's goals. With these guideposts in mind, idea generators should begin their program design in the form of a wireframe.

Wireframe Development

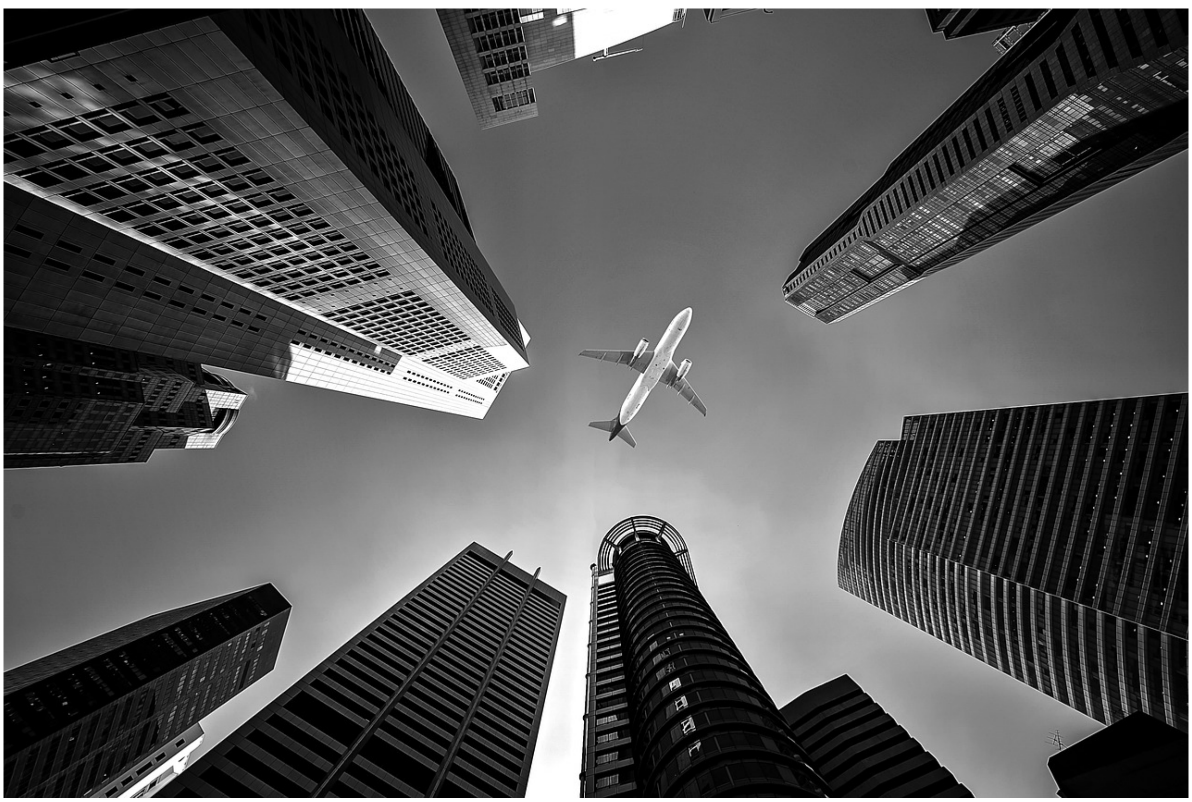
The first phase in ARPA program development is creating a program wireframe, which is an outline of a potential program that captures key components for consideration to assess the program's fit and potential impact. The template below shows the components characteristic of a program wireframe.



To create a fully fleshed-out wireframe, program directors work backward by first envisioning a **future state** that would be truly transformational for society and across sectors if it were to be realized. Then, they identify a clearly-articulated **problem** that needs solving and is hindering progress toward this transformational future state. During this process, PDs need to conduct extensive root cause analysis to consider whether the problem they've identified is exacerbated by policy, regulatory, or environmental complications—as opposed to those that technology can already solve. This will inform whether a problem is something that ARPA-I has the opportunity to impact fundamentally.

Next, program directors identify a promising **opportunity**—such as a method, approach, or technology—that, if developed, scaled, and implemented, would solve the problem they articulated and help achieve their proposed future state. When considering a promising opportunity, PDs must assess whether it front-runs other potential technologies that would also need developing to support it and whether it is feasible to achieve concrete results within three to five years and with an average program budget. Additionally, it is useful to think about whether an opportunity considered for program development is part of a larger cohort of potential programs that lie within an ARPA-I focus area that could all be run in parallel.

Most importantly, before diving into how to solve the problem, PDs need to articulate what has prevented this opportunity from already being solved, scaled, and implemented, and what **explicit role or need there is for a federal R&D agency** to step in and lead the development of technologies, methods, or approaches to incentivize private sector deployment and scaling. For example, if the private sector is already incentivized to, and capable of, taking the lead on developing a particular technology and it will achieve market readiness within a few years, then there is less justification for an ARPA intervention in that particular case. On the other hand, the prescribed solution to the identified problem may be so nascent that what is needed is more early-stage foundational R&D, in which case an ARPA program would not be a good fit. This area should be reserved as the domain of more fundamental science-based federal R&D agencies and offices.



One example to illustrate this maturity fit is DARPA investment in mRNA. While the National Institutes of Health contributed significantly to initial basic research, DARPA recognized the technological gap in being able to quickly scale and manufacture therapeutics, prompting the agency to launch the Autonomous Diagnostics to Enable Prevention and Therapeutics (ADEPT) program to develop technologies to respond to infectious disease threats. Through ADEPT, in

2011 DARPA awarded a fledgling Moderna Therapeutics with $25 million to research and develop its messenger RNA therapeutics platform. Nine years later, Moderna became the second company after Pfizer-BioNTech to receive an Emergency Use Authorization for its COVID-19 vaccine.

Another example is DARPA's role in developing the internet as we know it, which was not originally about realizing the unprecedented concept of a ubiquitous, global communications network. What began as researching technologies for interlinking packet networks led to the development of ARPANET, a pioneering network for sharing information among geographically separated computers. DARPA then contracted BBN Technologies to build the first routers before becoming operational in 1969. This research laid the foundation for the internet. The commercial sector has since adopted ARPANET's groundbreaking results and used them to revolutionize communication and information sharing across the globe.

Wireframe Refinement and Iteration

To guide program directors through successful program development, George H. Heilmeier, who served as the director of DARPA from 1975 to 1977, used to require that all PDs answer the following questions, known as the Heilmeier Catechism, as part of their pitch for a new program. These questions should be used to refine the wireframe and envision what the program could look like. In particular, wireframe refinement should examine the first three questions before expanding to the remaining questions.

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What is new in your approach, and why do you think it will be successful?
- Who cares? If you are successful, what difference will it make?
- What are the risks?
- How much will it cost?
- How long will it take?
- What are the midterm and final "exams" to check for success?

Alongside the Heilmeier Catechism, a series of assessments and lines of questioning should be completed to pressure test and iterate once the wireframe has been drafted. This refinement process is not one-size-fits-all but consistently grounded in research, discussions with experts, and constant questioning to ensure program fit. The objective is to thoroughly analyze whether the problem we are seeking to solve is the right one and whether the full space of opportunities around that problem is ripe for ARPA intervention.

One way to think about determining whether a wireframe could be a program is by asking, "Is this wireframe science or is this science fiction?" In other words, is the proposed technology solution at the right maturity level for an ARPA to make it a reality? There is a relatively broad range in the middle of the technological maturity spectrum that could be an ARPA program fit, but the extreme ends of that spectrum would not be a good fit, and thus those wireframes would need further iteration or rejection. On the far left end of the spectrum would be basic research that only yields published papers or possibly a prototype. On the other extreme would be a technology that is already developed to the point that only full-scale implementation is needed. Everything that falls between could be suitable for an ARPA program topic area.

Once a high-impact program has been designed, the next step is to rigorously pressure test and develop a program until it resembles an executable ARPA program.

Applying ARPA Frameworks to Transportation Infrastructure Challenges

By using this framework, any problem or opportunity within transportation infrastructure can be evaluated for its fit as an ARPA-level idea. Expert and stakeholder idea generation is essential to creating an effective portfolio of ARPA-I programs, so idea generators must be armed with this framework and a defined set of focus areas to develop promising program wireframes. An initial set of focus areas for ARPA-I includes safety, climate and resilience, and digitalization, with equity and accessibility as underlying considerations within each focus area.

There are hundreds of potential topic areas that ARPA-I could tackle; the two wireframes below represent examples of early-stage program ideas that would benefit from further pressure testing through the program design iteration cycle.

Note: The following wireframes are samples intended to illustrate ARPA ideation and the wireframing process, and do not represent potential research programs or topics under consideration by the U.S. Department of Transportation.

Next-Generation Resilient Infrastructure Management

Problem

Roads and bridges need continuous repair, replacement, and rebuilding every 40-50 years. It costs trillions of dollars globally per year. Corrosion of metals and durability of concrete are major drivers. Demand for these materials as a big impact on the climate (8-10% of greenhouse gas (GHG) emissions).

Opportunity

There are technologies and processes–such as low carbon materials, pre-manufactured systems for on-site assembly, and smart sensors–that can extend the life of existing infrastructure and improve climate resiliency, but are disparate and would benefit from synthesis for greater impact.

Program Objective

Develop a full life-cycle resilient infrastructure management system–made up of a suite of Hardware/Software tools–that is fully deployable at a local level to help agencies plan, build, and monitor physical infrastructure.

Future

New roads and bridges are built to be more durable, climate resilient, cost-effective, and contribute less to global GHG emissions.

A Digital Inventory of Physical Infrastructure and Its Uses

Problem

Public agencies cannot conduct infrastructure planning and building efficiently because they lack standard definitions and usage data for assets in the built environment.

Opportunity

The targeted and integrated use of data standards, sensors, computer vision, satellite imaging, and video analytics can be applied to provide public agencies with information on physical infrastructure and its use.

Program Objective

Create a digital inventory of physical infrastructure assets to allow agencies to categorize and describe assets. The usage data collected from these assets can then be digitized to show how goods and people move through a transportation system.

Future

Public agencies can more efficiently tie the allocation of resources for infrastructure design and deployment to standardized knowledge of assets and usage data.

Wireframe Development Next Steps

After initial wireframe development, further exploration is needed to pressure test an idea and ensure that it can be developed into a viable program to achieve "moonshot" ambitions. Wireframe authors should consider the following factors when iterating:

* The Heilmeier Catechism questions (see page 14) and whether the wireframe needs to be updated or revised as they seek to answer each of the Heilmeier Catechism questions
* Common challenges wireframes face (see page 11) and whether any of them might be reflected in the wireframe

* The federal, state, and local regulatory landscape and any regulatory factors that will impact the direction of a potential research program
* Whether the problem or technology already receives significant investment from other sources (if there is significant investment from venture capital, private equity, or elsewhere, then it would not be an area of interest for ARPA-I)
* Adjacent areas of work that might inform or affect a potential research program
* The transportation infrastructure sector's unique challenges and landscape
* How long will it take?
* Existing grant programs and opportunities that might achieve similar goals

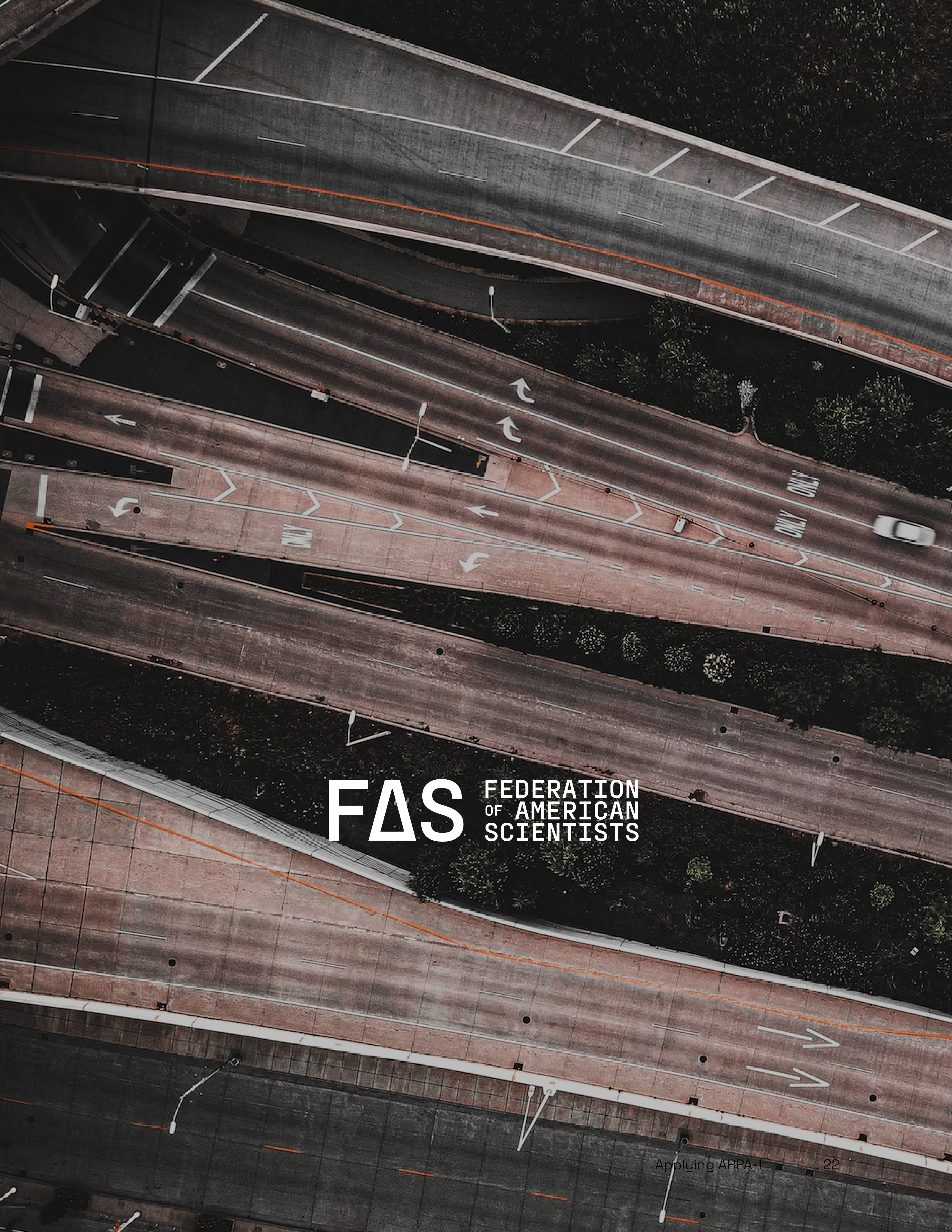
Wireframes are intended to be a summary communicative of a larger plan to follow. After further iteration and exploration of the factors outlined above, what was first just a raw program wireframe should develop into more detailed documents. These should include an incisive diagnosis of the problem and evidence and citations validating opportunities to solve it. Together, these components should lead to a plausible program objective as an outcome.

Conclusion

The newly authorized and appropriated ARPA-I presents a once-in-a-generation opportunity to apply a model that has been proven successful in developing breakthrough innovations in other sectors to the persistent challenges facing transportation infrastructure.

Individuals and organizations that would work within the ARPA-I network need to have a clear understanding of the unique circumstances, challenges, and opportunities of this sector, as well as how to apply this context and the unique ARPA program ideation model to build high-impact future innovation programs. This community's engagement is critical to ARPA-I's success, and the FAS is looking for big thinkers who are willing to take on this challenge by developing bold, innovative ideas.

To engage with the FAS by sharing insights, expertise, or developing a transportation infrastructure program design, please visit: https://fas.org/initiative/advanced-research-at-dot.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