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Request for Information on the National Digital Twins R&D Strategic Plan

Readiness Resource Group (RRG)

Digital Twins R&D Strategic Plan: National Use Case
Digital Engineering the Defense Maglev Network

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Topics: **Artificial Intelligence**; **Business Case Analysis; Ecosystem; Standards; Sustainability**

Abstract

We address the importance of a) developing national use cases in formulating the National Science Foundation (NSF) Digital Twin Research and Development Strategic Plan, and b) including a priority use case for the emerging industrial sector of superconducting magnetic levitation technologies, and the concept of digital engineering a national Defense Maglev Network (DMN).

A Defense Maglev Network is a national security and economic benefit, the precursor to an Interstate Maglev Network, and a stimulus for a new industrial ecosystem and supply chain. The network offers cross-cutting benefits to the defense industrial base (DIB), transportation and logistics infrastructure competitiveness, and restoration of U.S. technological superiority.

Digital Engineering (DE) is now underpinning large systems design, development, implementation and sustainability with anticipated productivity, rapid transition to manufacturing, accelerated test and systems validation, and dramatically reduced lifecycle costs. Transformations in digital engineering will dramatically reduce the time from concept to full-scale production-ready systems.

The Recommendation

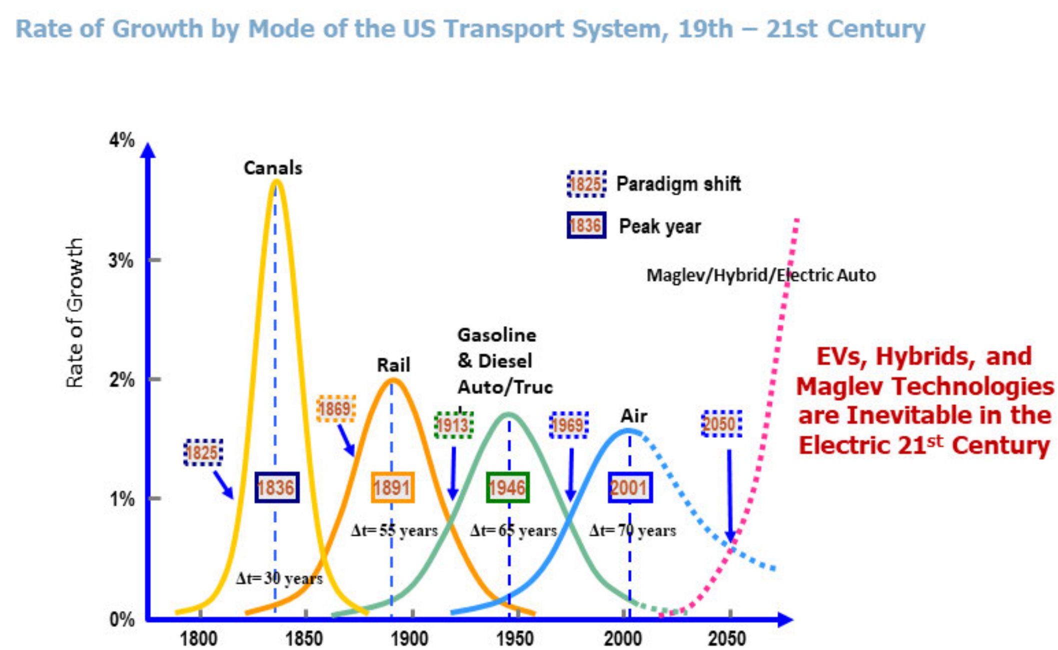
An extraordinarily rare opportunity exists to leapfrog our international competitors by investment in a comprehensive Digital Twins (DT) program initiative focused on multiple national use cases. As a priority use case, we seek to advance our transportation infrastructure because it is foundational to national security, economic competitiveness, and societal resilience.

We recommend undertaking a digital engineering development effort to enable implementation of the first transcontinental ultra-high-speed, environmentally benign, and energy conserving logistics network based on U.S. designed and manufactured superconducting maglev technologies. The initial implementation of such a network should support priority defense and homeland security needs to connect critical nodes for readiness, response, and recovery from a spectrum of threats and hazards, to enhance mobilization and deployment options, and to validate the operational competitiveness and resilience for what could become a more extensive national interstate maglev network serving all Americans.

Background

America led the world in transportation. In the 1800s we developed canals like the Erie, Robert Fulton invented the steamboat, and we built the Transcontinental Railroad. In the 20th Century, we led the way with Henry Ford's automobiles, Wright Brothers airplane, Panama Canal, jet airliners, Eisenhower's 45,000-mile Interstate Highways, our Space Program, and the Internet. Existing modes of transportation have reached their practical, cost-effective limits. Railroads have changed little in over a century. Highways are increasingly costly to maintain, congested and unsafe in metropolitan areas. Sustaining the Highway Trust Fund is a well-known challenge.

Exhibit 1 portrays the rate of growth of various modes of transport within the United States.



Source: adapted from J.H. Ausubel, C. Marchetti, and P. Meyer (1998) "Toward Green Mobility: the Evolution of Transport", European Review, Vol. 6, No. 2, pp. 137-156.

Exhibit 1 The Dynamic Evolution of U.S. Transportation

America's adversaries and near-peer competitors are investing in superconducting magnetic levitation (SCM) technologies for logistics, surface transportation, and grid-scale energy storage. This idea was first introduced by two American scientists in the 1960s and has largely been ignored by the United States. Following the model of previous American technology successes, we propose the creation of a DMN to support the nation's homeland security and defense requirements with a continent-wide advanced logistics infrastructure.

Superconducting Maglev was invented in 1966 by Gordon Danby, Ph.D. and James Powell, Sc.D. at Brookhaven National Laboratory. Learning of their inventions, scientists and engineers from Japan and other countries visited them to obtain details. Other governments implemented Maglev systems, and these are now operational in China, South Korea, and Japan.

We face grand challenges in modernizing critical infrastructure. Facing those challenges without considering the benefits of SCM runs the risk of hobbling the U.S. economy for decades to come, especially as competitors in China, Japan, South Korea, India, and the European Union build out their maglev infrastructures. Danby and Powell's first-generation SCM has been demonstrated by Japan and holds the world's speed record of 375 miles per hour (mph) for guided surface transport.

Military logisticians are aware of the history of the Interstate Highway System (IHS), starting with Dwight Eisenhower accompanying a 1919 Army expedition of trucks and tanks across the continental United States. It took 62 days to travel 3,200 miles, with roads in the west described by Eisenhower as a "succession of dust, ruts, pits, and holes." During World War II, the future president also perceived the utility of the German Reich's autobahn for Nazi military supplies movement. There was opposition in Congress as to the cost of modernizing the nation's road infrastructure but use for defense helped justify the passage of the Federal Aid Highway Act of 1956 and the start of IHS construction in the same year.

The already obtained rights-of-way (ROW) of the IHS strongly influenced the vision of the late Drs. Powell and Danby for the development of a continent-wide (to include some Canadian destinations) high-speed elevated freight and passenger surface transportation network based on their invention of second-generation superconducting magnetic levitation (SCM), known as Maglev 2000. Many stations on this envisaged 29,000-mile network would be essential for military and disaster evacuation movements, which would be made at speeds exceeding 300 mph.

Concerning rail travel, the United States is in a position akin to telecommunications in (so-called) Third World nations a few decades ago. Rather than slowly advance from not even having telephones to setting up the typical telephone infrastructure, people even in remote areas received cell phone infrastructure and joined the developed world in individual communications. For the U.S., there is no need to advance from its current state—with few trains even traveling 100 mph—to European steel-on-steel systems that can reach 200 mph. It is time to "leapfrog" steel-on-steel and move directly to an elevated maglev system and its 325 mph cruising speed.

The DMN, which will become an essential element of the Defense Industrial Base (DIB), must be protected as an asset under the Defense Industrial Base Critical Infrastructure Sector Security Plan. Just as military bases and the nation's airports and seaports are heavily protected, the DMN network must have strong security, (some) redundancy, avoidance of a single point of failure (with alternate routing), and an assured supply of critical raw materials along with back-up sources for those materials. IHS primarily serves civilian passenger and freight vehicle purposes; the maglev network will do the same caveated for emergency appropriation by military authorities.

It is difficult to perceive future threats within and along the borders of CONUS. What if a situation, for example, on the southern border requires a response the size of an Army division (i.e., 10,000-15,000 soldiers) from Fort Riley, Kansas or a Marine division (i.e., 22,000 Marines) from Camp

Pendleton, California—and their associated ground attack equipment assets? Military convoys on the IHS typically average 40 mph. DMN can move troops and cargo at EIGHT times that speed.

Defense Maglev Network would support:

- Rapid mobilization of troops and equipment at eight times the current speed.
- Much faster supply container movement from and to sea, air, and land ports in an all-weather resilient infrastructure.
- Expedited distribution of materiel from Defense Logistics Agency depots, with military command and control exercised by the U.S. Transportation Command.
- Implementation of a Medical Response Disaster Train for large-scale patient evacuation away from mass casualty incidents to higher levels of care.

Exhibit 2 illustrates the concept for construction of the national maglev network. Three Waves of Construction Blue, Green, and Red to be completed in about 20 years.

Inside a given metropolitan area, Maglev will access existing rail networks, by adapting existing railroad trackage for Maglev travel. The adaptation consists of attaching thin polymer concrete panels encapsulating loops of aluminum to the crossties.

Maglev Network	States In Network	Population of States in Network (millions)	Population Living Within 15 Miles of Stations (millions)	Route Miles in Network
First, Second and Third Waves Completed	48 plus Toronto, Montreal & Vancouver	315 includes Toronto, Montreal & Vancouver	232 includes Toronto, Montreal & Vancouver	29,000
74% of the population in States live within 15 Miles of a Station				

Exhibit 2 Notional Implementation Timeline

The Challenge and Opportunity

The evolution of maglev technology reaches back to the pioneering work of Michael Faraday, Heike Onnes, Nikola Tesla, Robert Goddard, and Emile Bachelet. The invention of *superconducting* maglev for transport rests with the tireless work of James Powell, Sc.D., and Gordon Danby, Ph.D., both distinguished scientists from the Brookhaven National Laboratory. The Japanese government invested in developing Powell and Danby's first-generation design and built the full-scale system at their Yamanashi Test Facility. The United States failed to seize the opportunity to take global leadership in this technology and now we have competitive solutions emerging from China, India, Korea, Germany, Poland, Italy, and Japan. Powell and Danby's work continued, enabling development of the 2nd generation maglev system. Powell and Danby were awarded the Franklin Medal of Engineering for their contributions to transportation. They share this honor with Albert Einstein, Niels Bohr, Alexander Graham Bell, Thomas Edison, Pierre and Marie Curie, Nikola Tesla, Wernher Von Braun, and Stephen Hawking.

Full-scale components for the Defense Maglev Network – superconducting magnets, guideway panels, guideway beams, vehicle concepts, etc. – have been successfully fabricated and tested and their costs validated. The next step is to assemble the components into operating vehicles and test them on a guideway track to demonstrate third-generation SCM's unique capability to electronically switch (vice mechanical guideway switching), levitate heavy freight (loaded long-haul trucks), and switch between the high-speed mainline guideway to Maglev-adapted conventional railroad tracks for accessing densely built population centers and using existing rail tunnels, bridges, and terminals.

Maglev Architecture

Maglev vehicles are magnetically levitated above and propelled along guideways at hundreds of mph, without mechanical contact. They do not emit pollutants or greenhouse gases, are noticeably quiet, comfortable, and safe. The fundamental design innovations underlying all SCM systems present today were invented by Powell and Danby between the years 1966 and 1971 during their service to the Brookhaven National Laboratory. These innovations include electric dynamic stabilization (EDS), null-flux loop geometry (NFLG), and linear synchronous motors (LSM).

Between 1966 and 1996, Japan conducted a multi-billion dollar R&D program to develop SC maglev into a workable system. Between 1997 and 2015, at the Yamanashi test track, Japan entered into a testing phase for the vehicle and guideway configurations that would become their final commercial maglev system. During testing the commercial test vehicles travelled with a 100% safety record over 100,000 miles, carrying more than 10,000 passengers, at speeds up to 375 mph. In 2015, Central Japan Railways began construction of their Chūō Shinkansen maglev line between Tokyo and Nagoya.

The DMN DT should describe the design of a North American logistics network that maximizes elevated, narrow-beam guideways, minimizing at-grade disruptions enhancing speed of delivery and reducing safety hazards. Reliability is enhanced by a design that has almost no moving parts, making operation and maintenance a small component of the life cycle system cost.

New supply chains and manufacturing opportunities defined in the DMN Digital Twin will strengthen the Defense Industrial Base (DIB):

- Manufacturing
  - Manufacture of Third-Generation Magnet Assemblies (leveraging high-temperature superconductors and Cryocooler technologies applicable to other defense applications)
  - Manufacture of Superconducting Wire & Cable Materials (renaissance of a production capability that has been offshored for decades)
  - Manufacture of Roll-on/Roll-off Freight Ferry Vehicles (reinforcing aerodynamics and aviation engineering expertise)
  - Additive Manufacturing Solutions.

- Construction
  - Green Concrete within prefabricated piers, stanchions, and guideway beams
  - Passive Maglev Loop Panels within advanced polymer concrete casings
  - Architect and Engineering (A&E) Design and Build for Intermodal Operations, On-Site Pier Footings, and Transfer Stations.

- Integration
  - Command, Control and Communications, e.g., position and speed control, switching, emergency response, failure management, artificial intelligence (AI)/machine learning (ML) for network optimization and route planning
  - Integration with Steel Wheel Railroad Operations (Maglev Emplacement on Railroad Infrastructure)
  - Advanced Safety and Security Management (intrusion detection systems; AI-enabled security surveillance and monitoring; perimeter protection; safe escape provisions; ballistics protective measures; cybersecurity).

Key Benefits of Digital Engineering (DE)

Ecosystem: The NSF initiative driving the Digital Twins R&D recognizes the long-term benefits of adopting the digital engineering best practices:

- Improves the quality and the speed of system and system-of-system (SoS) mission capability deliveries.
- Enhances understanding of engineering designs and improves decision making, including all hardware and software configuration, system test and evaluation.
- Collapses the cycle time by moving the right side of the Systems Integration V to the left, enabling early system understanding, architecture design trades, and detecting defects early in the design phase.
- Reduces lifecycle cost through systematic design reuse and lowering transaction cost.
- Improves the ability of "owning the technical baseline," configuration and change management, better requirement definition and traceability, and rapid engineering responses.
- Enables knowledge management and communication and across stakeholder communities and acquirer-supplier teams.

A Reference Model or Framework under the auspices of a government-wide DT R&D portfolio would validate commercial and government developed databases and software applications used to generate, visualize, analyze, and validate designs. This approach would incentivize the building of a common architecture unlike the incremental development designs and build programs of past decades.

Standards: The excellent standards development expertise of the National Institute of Standards and Technology (NIST) within the U.S. Department of Commerce, to include its cybersecurity guidance, in partnership with DOT on system requirements, feasibility, route planning and NASA on other technical challenges would be value added. Coordination with the Environmental Protection Agency (EPA) and Occupational Safety & Health Administration (OSHA) would validate the benign environmental, health and safety (EH&S) aspects of the proposed maglev transport for both logistics and passengers. A panoply of federal departments and agencies all have important contributions to make to a DMN Digital Twin prototype in cooperation with industry and the academic research community. Standards for guideway, control systems, and emplacement over conventional railroad trackage each require novel standards development.

Digital engineering approaches also support rapid implementation of innovations within a connected digital end-to-end enterprise. Models can provide a precise and versatile representation of a system, phenomenon, entity, or process. In early phases of the lifecycle, models enable virtual exploration of solutions before actually instantiating them. Over a solution's lifecycle, models mature and become useful replicates to physical counterparts for virtual testing and sustainment.

Models will be used as the basis for defining, evaluating, comparing, and optimizing alternatives and making decisions. This paradigm shift will fundamentally change the current practice of accepting documents to accepting models and provides the technical underpinnings for acquisition domains and functional areas. Users can generate various views using a shared network of models and data to offer coherent digital artifacts, while reducing time-consuming effort and rework.

The fundamental tools for the DE endeavor include:

- Model-Based Systems Engineering (MBSE): The use of a modeling and simulation approach as theprimary means of information exchange and to create digital threads.
- Integrated Product Lifecycle Management and Supply Chain Management: Streamlining the lifecycle process of design, build, integration, and testing to connect the desktop to the testing laboratory and the manufacturing floor.
- Cloud Services: Implementing secure cloud services, providing a multi-security enterprise cloudenvironment, and driving cloud migration.
- AI/ML: The use of large language models (LLMs) and other algorithmic models in route planning and network optimization, and structural monitoring.
- VR/AR/MR: State-of-the-art Virtual Reality (VR)/Augmented Reality (AR)/Mixed Reality (MR)technology for immersive and collaborative digital engineering, design reviews, training, and application of digital twins technology.

Business Case Analysis: Freight on highway trucks transported by Maglev roll-on/roll-off ("Ro-Ro") vehicles is projected to cost 10 cents per ton-mile, compared to 30 cents a ton-mile by highway.

Passengers travel on Maglev vehicles will cost 4 cents per passenger mile, compared to 15 cents per mile by air, and 40 cents per mile by highway.

Transporting trucks by maglev will also reduce:

- Highway deaths, injuries, and accidents
- Highway congestion
- Emissions of toxic pollutants and greenhouse gasses
- Cost of transporting goods
- Cost of repairing highway surfaces and infrastructure.

Sustainability: Benefits of an Interstate Maglev Network include:

- Decrease of transportation-related exhaust emissions by 50% from current levels by 2050
- Decrease of transport and logistics costs in the U.S. and the world, economically accelerating both developed and emerging economies by substantially lowering the price of goods and travel
- Fostering of smart growth by using the network infrastructure to serve as a low-cost means for distributing electric power and protected, secure broadband communications
- Beginning a sustainable global transportation infrastructure boom to attract tens of trillions of dollars of investment in both developed and emerging economies in electric transport for both logistics and passenger travel, with America setting the technical standards for global expansion of the network.

Conclusion

Defining a national network requires coordinated governmental, industrial, and academic leadership presenting a once in a century opportunity to mobilize technical expertise in partnership to implement the largest infrastructure system design endeavor in the nation's history.

Using the Defense Maglev Network as the case study advances U.S. leadership in both digital engineering practices and the infrastructure development. Today this nascent industrial opportunity is aggressively being pursued by the European Union (especially Poland), China, Japan, Korea, and India. Failure to undertake this effort assures the loss of this critical infrastructure domain and market opportunity to our near peer competitors and adversaries.

The preliminary DMN would have collateral benefits for the transportation, energy, and communications infrastructure sectors. A resilient design of prefabricated guideway can support secure conduit for fiberoptic cables and power for widely distributed EV charger stations along the network route. This will extend high-speed broadband service to thousands of locations in the dark today and will add integrated transportation services for EV mobility. Thus, the DMN will provide additional resilience to our communications and power distribution architecture.

Ignoring key technologies such as Superconducting Maglev underscores the growing deficit in our logistics and technology preeminence and the gulf between our applied research and that of our adversaries and competitors who are implementing these systems in plain view. It is noteworthy that applied research in maglev for logistics will enable breakthroughs for its future use in grid-scale energy storage and in extremely low-cost electromagnetic space launch infrastructure. America's failure to develop its inventions reduces our competitiveness in science, engineering, and logistics.

The Digital Twins R&D Strategic Plan should highlight multiple national use cases within which the value of digital engineering can create a resilient repository of knowledge that will accelerate the testing and implementation of new systems and services, dramatically reducing time from concept to operational cutover. Those use cases that are cross-cutting in terms of advancing emerging technologies, supply chains, and research domains should be prioritized. We propose that the Defense Maglev Network is a viable, priority national use case of merit and should be highlighted within the NSF Digital Twins R&D Strategic Plan.

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