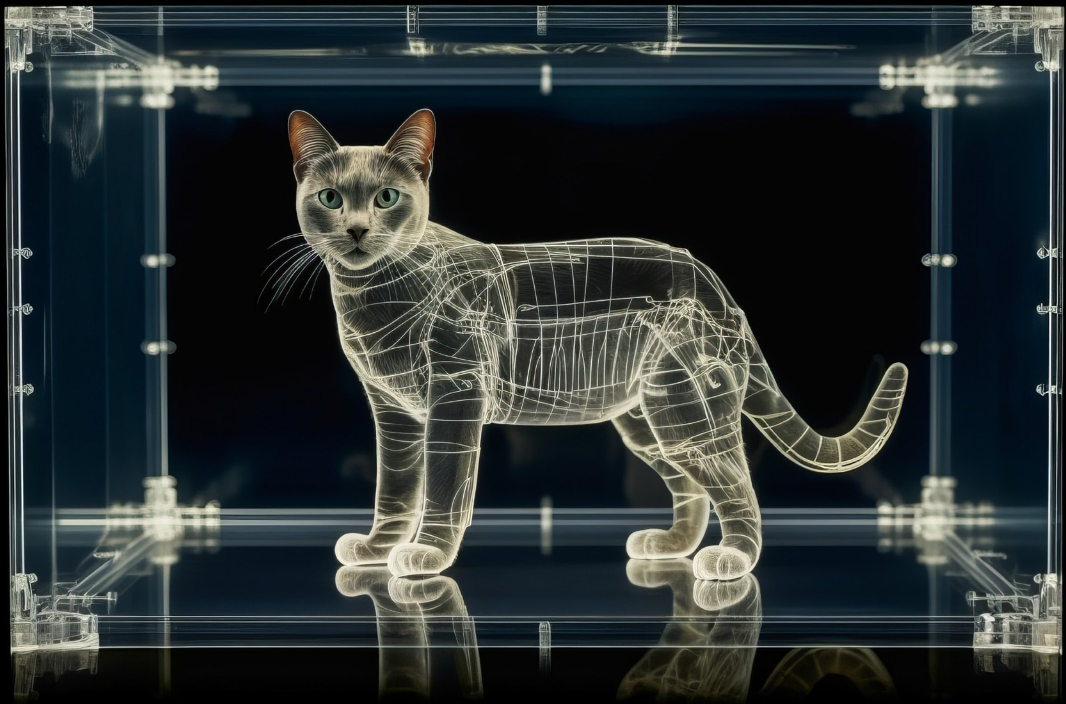


Quantum Technologies in Transportation

November 2024

Daniel A. LeMaster
Senior Scientist, Highly Automated Systems Safety Center of Excellence

Prachi Vakharia
Strategic Advisor, Advanced Research Projects Agency – Infrastructure

Office of the Assistant Secretary for Research and Technology
U.S. Department of Transportation
1200 New Jersey Avenue SE, Washington, DC 20590

U.S. Department of Transportation

Highly Automated Systems Safety Center of Excellence

ADVANCED RESEARCH PROJECTS AGENCY • INFRASTRUCTURE

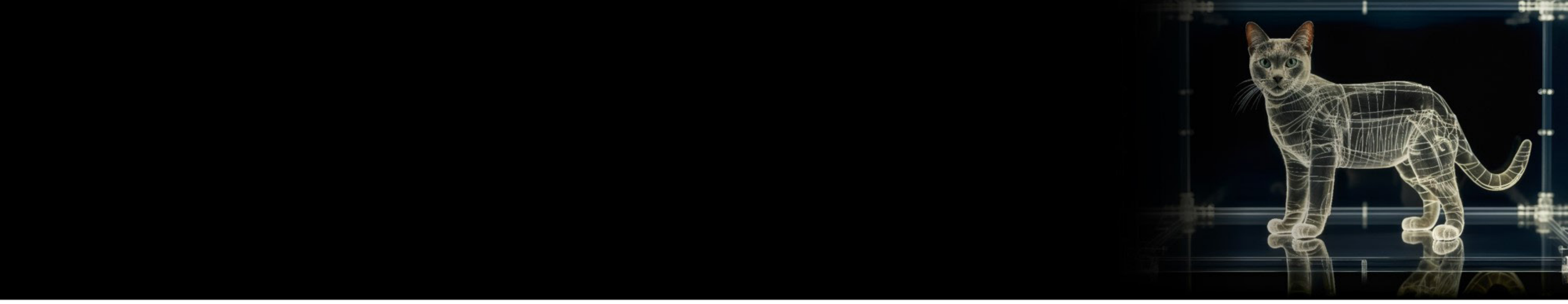
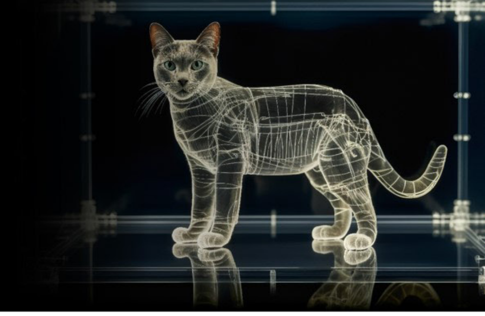


Table of Contents



Executive Summary

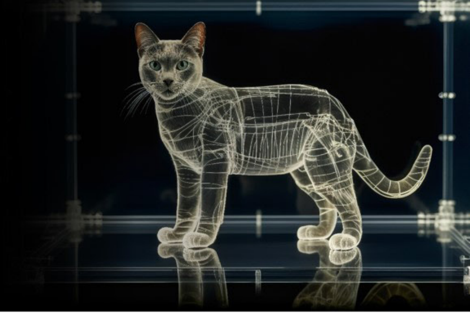
Quantum technologies for networking, sensing, and computing will transform the global economy. In July 2024, the U.S. Department of Transportation (USDOT) *Quantum Technologies in Transportation Workshop* examined the near- and long-term opportunities for quantum sensing and computing to make our transportation system more safe, competitive, equitable, and sustainable. The workshop included more than 180 in-person and online participants spanning USDOT operating administrations and quantum professionals from industry, academia, and other government agencies. The purpose of this report is to summarize the findings of the workshop and to identify next steps we can take as a Department to integrate quantum technology into transportation policy, planning, regulation and standards, economic development, enforcement and inspections, research, and outreach.

Quantum computers have the potential to solve some problems much faster than computers today in areas like optimization, machine learning and artificial intelligence, and materials science. This quantum advantage has been explored in problems like the placement of electric vehicle charging stations and 5G cell towers, emergency evacuation planning, and flash flood predictions. Workshop participants identified 18 priority areas for which quantum computing has the potential to transform transportation with applicability across all modes. Examples include optimizing networks for safety, efficiency, and accessibility for all users; designing more resilient infrastructure with extended useful life; and mitigating crashes and improving survivability.

Depending on the application, the advantages of quantum sensors over their classical counterparts include higher sensitivity; increased long-term stability and accuracy; the ability to self-calibrate; and reduced size, weight, and power. Quantum sensors are commercially available or are rapidly maturing for use in communications, finance, medicine, resource exploration, and chemical detection. Maturation is particularly evident in each of the constituent capabilities included in Positioning, Navigation, and Timing (PNT). Workshop participants identified seven categories of quantum sensing with applicability to all modes of transportation. Examples include assured safe navigation for planes and ships when GPS is unavailable or untrustworthy; leak and corrosion detection for pipelines, rail, and trucking; and stable, long-duration monitoring for infrastructure health.

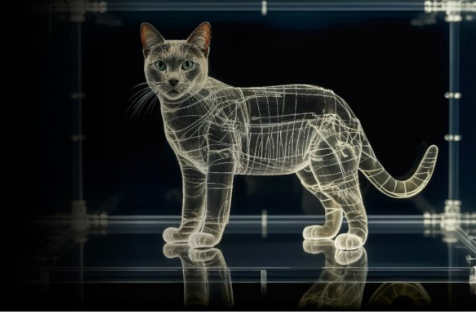
USDOT can efficiently leverage advancements in quantum technologies without sacrificing attention to near-term needs. Proposed first steps include the following:

1. Participate alongside the Departments of State, Energy, Commerce, and Defense, along with other federal partners like NIH and NASA, on the National Science and Technology Council's Subcommittee on Quantum Information Science (pending reauthorization).
2. Develop a quantum technology assessment framework to anticipate vulnerabilities and identify in-house research questions that support future regulatory needs.



3. Evaluate the use of quantum optimization for funding, planning, building, and operating large projects for economic, equity, climate, and sustainability impacts.
4. Encourage quantum innovation and reduce uncertainty in the transportation sector by publishing guidance on how and when these emerging technologies intersect with existing enforcement authorities.
5. Become savvy consumers of quantum technology through direct research investments in algorithm prototypes and evaluations of sensing technologies for transportation use cases.
6. Create and maintain a quantum use case knowledge base, including metrics and benchmarks for mapping quantum technology performance to transportation domain requirements.
7. Create a healthy dialogue with the quantum technology community using the same tools we use to communicate within the transportation research community.

Our workshop identified transformative opportunities in which quantum technologies may serve each mode of transportation. By starting now, we can be ready when our Nation experiences a quantum watershed moment, like for artificial intelligence in 2023, with a small cadre of transportation domain experts cross-trained in quantum technologies, a limited investment in foundational projects, and an established network of quantum experts.



Introduction

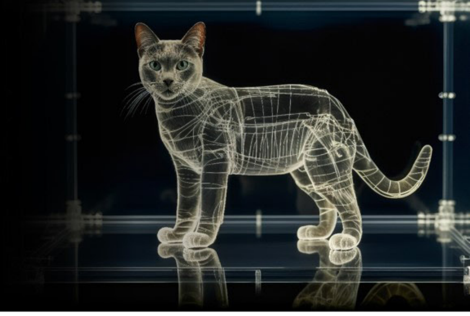
The U.S. Department of Transportation (USDOT) Research, Development, and Technology (RD&T) Strategic Plan defines ambitious goals for transforming our Nation's transportation system—making it more safe, competitive, equitable, and sustainable. In July 2024, the USDOT's *Quantum Technologies in Transportation Workshop* took a step toward evaluating quantum technologies as means to these ends. The workshop included contributions of both quantum professionals from across the country and transportation domain experts from across the Department. The purpose of this report is to interpret the results of the workshop for USDOT decision-makers and to provide recommendations for departmental engagement with these transformative technologies.

At the introduction of our workshop, USDOT Chief Information Officer, Mr. Cordell Schachter, stated that quantum computing may be more important to transportation than artificial intelligence. He challenged the attendees to understand how quantum computing can improve transportation safety and to be prepared to defend against potential malicious uses of quantum computing by adversaries. Mr. Schachter expressed his excitement that this is happening within USDOT and expects it will be the first of many conversations.

In her introductory remarks, Dr. Gretchen Campbell, Deputy Director of the National Quantum Coordination Office at the White House Office of Science and Technology Policy, highlighted that quantum sensors are one of the areas of quantum technology, along with quantum computing and quantum networking, that could enable real-world transformation in the near future. She mentioned the decades of federal funding that has allowed quantum sensors to enter the market and find end use cases. Dr. Campbell emphasized the importance of engaging partners like USDOT to identify relevant quantum technologies and explore how they could be developed to bring sensor prototypes to market more quickly.

These remarks from Mr. Schachter and Dr. Campbell set the stage for a day that brought together approximately 80 attendees in person and more than 100 attendees online. The distribution of registrants by USDOT operating administration (OA) is shown in Appendix A. A key feature of this workshop was the rapid exchange of ideas between quantum and transportation professionals, both in person and virtually. We thank all involved for a level of engagement that exceeded our expectations.

This report is organized into sections on quantum computing and quantum sensing. Each section includes a brief introduction to the technology drawn from the workshop presentations and discussions. We then provide transportation context through modal and strategic alignment of the use cases identified at the workshop. The report culminates in a call to action—next steps that we can take as a Department to integrate quantum technology into our Nation's transportation system, spanning policy, planning, regulation and standards, economic development, enforcement and inspections, research, and outreach. Recordings of our May 2024 webinar and July 2024 workshop are available at www.transportation.gov/hasscoe/highlights/quantum.



Quantum Computing

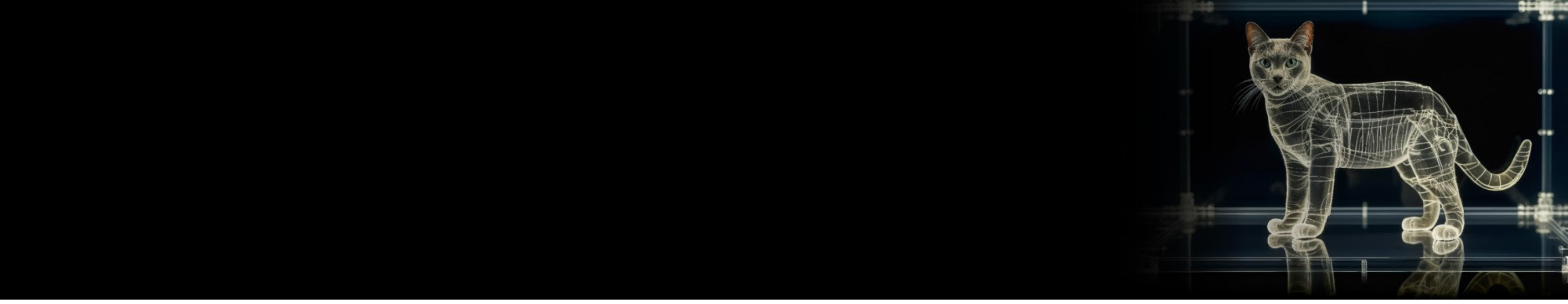
Quantum computers solve some problems in many fewer steps than classical computers. Widespread interest emerged when it became clear that quantum computers can theoretically defeat the encryption protocols that protect internet communications. Now it is clear that this technology also unlocks remarkable new opportunities in optimization, machine learning and artificial intelligence, materials science, and other disciplines that have the potential to transform the global economy, including the transportation sector.

What Is a Quantum Computer?

Quantum computers process parts of each problem for all possible inputs simultaneously, whereas classical computers must always process sequentially or spread the load across multiple processors. The building blocks of quantum computers are called qubits, and they obtain this ability by being manipulated into a state referred to as superposition. Special states of superposition, known as entangled states, correlate qubits such that, in theory, computational power increases exponentially with each additional qubit. Superposition and entanglement are uniquely quantum phenomena and are the key differentiators of this technology from classical computing.

Both gate-based and annealing quantum computers were discussed during the workshop. A quantum computer built on idealized gates could implement any quantum or classical algorithm. Annealing quantum computers are designed specifically to solve optimization problems. Gate-based quantum computers have scaled from 5 to 10 qubits in the recent past to 100 qubits at present and are predicted to reach somewhere between 1,000 and 10,000 qubits in the next few years. Annealing quantum computers with more than 5,000 special purpose qubits are available today. The computational space of quantum computers is truly enormous but also limited in an important way. Even though an idealized gate-based 160-qubit computer could represent more classical bits than there are silicon atoms on earth, these bits cannot be accessed directly as inputs or outputs in the nonquantum, macroscopic world of our everyday experience. This access limitation is the challenge of quantum information science (i.e., how to develop algorithms that make use of this profound computational capacity when only a small subset can be accessed and manipulated directly).

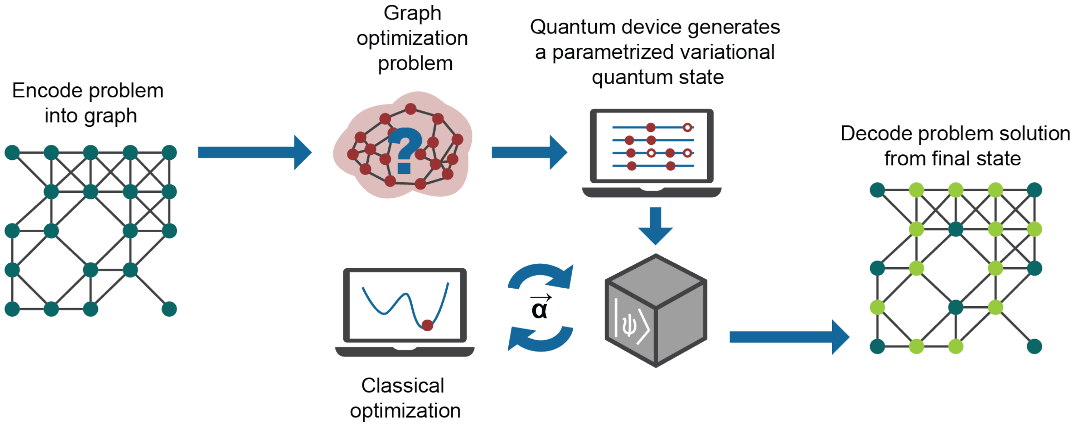
Qubit count is useful for conveying some sense of the pace of development, but these counts do not directly translate into performance. Qubits today are prone to noise that limits the number of useful calculations that can be achieved before errors occur. During the preworkshop webinar, Dr. William Oliver from MIT said current error rates are between 1 per 1,000 to 10,000 operations. Researchers are focused on developing more robust qubits and improving error-correcting algorithms, with a goal of one error per billion operations or better. We will return to a discussion of how and when quantum computers will scale after discussing current and future applications. Quantum computing technology is still maturing.



What Problems Are Quantum Computers Solving Today?

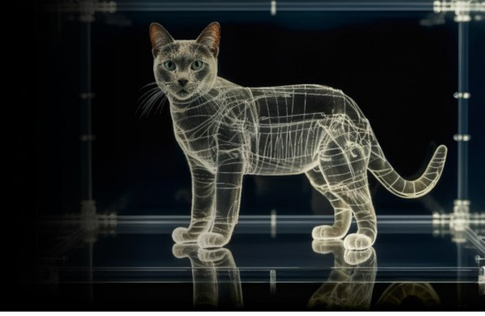
Workshop keynote speaker Dr. Mukund Vengalattore from the Defense Advanced Research Projects Agency (DARPA) provided an example of how quantum computers work side-by-side with classical computers in a hybrid configuration to solve optimization problems like in the placement of 5G cell towers and electric vehicle (EV) charging stations. This hybrid computing scenario is shown in Figure 1.

Figure 1. Examples of hybrid classical-quantum optimization in the Noisy Intermediate Scale Quantum era. (Source: M. Vengalattore, DARPA)



Additionally, keynote speaker Dr. Rob Hovsapian from the National Renewable Energy Laboratory at the U.S. Department of Energy (DOE) expanded on the EV charging optimization example to someday include alternative fuel corridor planning for evacuations in real time during emergencies. He characterized this as an optimization problem that can be run on today's quantum computers.

The panel discussion brought attention to several algorithms that have been demonstrated successfully on quantum computers, including in hybrid quantum-classical configurations. Dr. Franz Klein from the National Quantum Laboratory at the University of Maryland stated that quantum computers can solve graph optimization problems in the loop with digital twins. (As an example, graph optimization could be employed to find the combination of departure and arrival times in a multimodal transportation network that minimizes overall passenger transit times.) Mr. Thomas Ward from IBM explained how he is solving problems with quantum machine learning for flash flood prediction and generating results that exceed the capability of the classical approach. In another example, Mr. Ward discussed quantum machine learning in claims fraud for use by the insurance and financial industry. Ms. Allison Schwartz from D-Wave discussed how their quantum annealing computers have been used for tsunami evacuation planning. She stated that their hybrid solvers can currently incorporate up to 2 million variables for some problems.



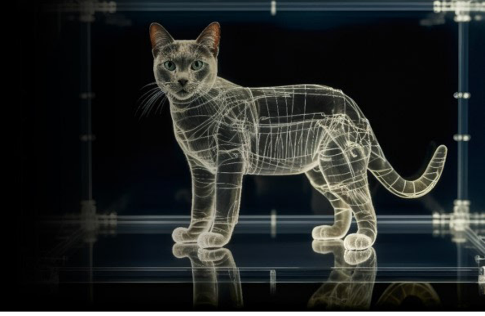
How Might Quantum Computing Change the Way USDOT Works In the Future?

Table 1 summarizes the quantum computing opportunities identified during the workshop and maps each to the transportation modes for which benefits may accrue. This modal matrix can be used to identify opportunities to coalesce around these topics, as will be discussed in Section IV.

Table 1. Ways that quantum computing might change transportation.

	Transportation Mode								
Quantum Opportunity	**Vulnerable Road Users**	**Passenger Vehicles**	**Rail**	**Trucking**	**Public Transit**	**Aviation**	**Infrastructure**	**Maritime & Seaway**	**Pipeline/ Hazardous Materials**
Predictive Safety and Maintenance	○	●	●	●	●	●	●	●	●
Routing/Scheduling/ Congestion Management	○	●	●	●	●	●	●	●	●
Supply Chain Optimization	○	○	●	●	○	○	○	●	○
Revenue Forecasting	○	○	○	○	●	○	●	●	○
Emergency Management/ Network Disruption Mitigation	●	●	●	●	●	●	●	●	○
Weather Forecasting	●	○	○	○	○	●	●	●	●
Materials Discovery	○	○	○	○	○	○	●	○	●
Battery Design	○	●	○	●	○	○	○	○	○
Corrosion Chemistry	○	○	●	○	○	○	●	●	●
Computational Fluid Dynamics	○	○	○	○	○	●	●	●	○
Fuel Efficiency	○	●	●	●	●	●	○	●	○
Smart Mobility Corridors	○	●	○	○	●	●	○	○	○
Close Call/Near Miss Mitigation	●	●	●	●	●	●	●	●	●
Cybersecurity	○	●	●	●	●	●	●	●	●
Human/Automated Vehicle Interaction Simulation	●	●	●	●	●	●	●	○	○
Last Mile/Curb Management Optimization	○	●	○	●	●	●	●	○	○
Crash Simulation	○	●	○	●	●	●	●	○	○
Connection Protection	●	●	●	●	●	●	●	●	●

● = identified opportunity; ○ = not applicable or unknown.



These opportunities are also readily distributed among the goals defined in the USDOT RD&T Strategic Plan. Here, we focus on safety, economic strength and global competitiveness, equity, climate, and sustainability. In the sections that follow, the applications listed in Figure 1 are placed in context by strategic goal. A simple vignette is added to solidify these ideas, which in an earlier era would seem unattainable.

Safety

Safety is USDOT's top priority.[1] Workshop participants identified predictive safety, maintenance, emergency management, network disruption mitigation, weather forecasting, close-call/near-miss mitigation, crash effects on battery chemistry, human–automation interaction simulation, and cybersecurity as opportunities for quantum computing to prevent injuries and fatalities.

These safety applications will be built on quantum/quantum-classical hybrid approaches to optimization and machine learning along with chemistry simulations and other simulations of complex systems. Transportation network-level applications are envisioned as a quantum layer operating on digital twins, enabling new forms of offline experimentation and real-time, online decision-making.

Economic Strength and Global Competitiveness

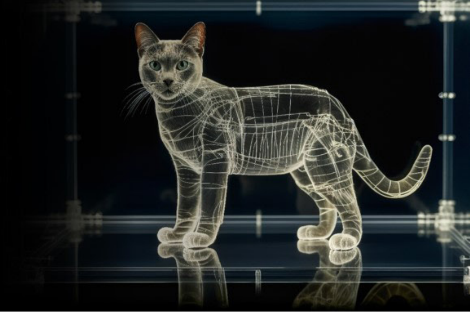
Our Nation's economic strength and competitiveness depends on modernizing our transportation systems and infrastructure. Workshop participants identified routing/scheduling/congestion management, supply-chain management, revenue forecasting, materials discovery, corrosion modeling, and last mile/curb management as opportunities for quantum computing to create jobs, grow an inclusive and sustainable economy, and improve quality of life.

Our Nation's economic strength and global competitiveness could benefit from quantum optimizers, artificial intelligence/machine learning, and material science. Similarly, researchers at IBM and Boeing have demonstrated quantum corrosion modeling capabilities that are more accurate than state-of-the-art approximate methods like density functional theory.[2]

Equity

The USDOT RD&T Strategic Plan proposes a grand challenge to create a transportation system that is safe, affordable, accessible, and convenient for all users. Smart mobility corridor optimization and connection protection are opportunities for quantum computing to optimize accessibility, deliver innovative services, and create wealth.

1 USDOT. 2024. "Safety: Keeping traveling Americans safe" [website]. Last accessed 10/30/24: https://www.transportation.gov/priorities/safety.
2 Davis, R. 2023. *Can quantum computers bring an end to corrosion?* [blog post]. Last accessed 10/30/24: https://www.ibm.com/quantum/blog/boeing-quantum-corrosion.



Quantum optimization can enable smart mobility and the supporting concept of connection protection so all users can confidently embark on a multimodal trip regardless of how or where the trip starts, traverses, or ends. This concept is an enormous real-time optimization problem where an individual action (e.g., a delayed bus, a missing wheelchair-accessible taxi) has ripple effects across transportation modes and into education, work, and healthcare. Combinatorial optimization problems like this are well-suited for improvement via quantum parallelism and are an active area of algorithm development.

Climate and Sustainability

USDOT aims to build resilient and sustainable transportation systems. The workshop participants identified congestion management, battery design, computational fluid dynamics, fuel efficiency, and weather event modeling as opportunities in which quantum computing can contribute to transportation system modernization that avoids exacerbation of climate change, is resilient to its effects, and prevents contamination of natural resources.

Computational fluid dynamics (CFD) provides an example of how quantum computing can reduce carbon dioxide emissions and support resilient infrastructure. CFD simulations are used to analyze infrastructure needs related to bridge scour and erosion and in fuel-efficient designs of ships, aircraft, and surface vehicles. CFD will benefit from quantum linear algebra methods applied to solving partial differential equations.

When Might USDOT Need to Be Ready?

Dr. Vengalattore emphasized the long road ahead before gate-based quantum computers transition out of the current noisy intermediate scale quantum (NISQ) era, characterized by qubits that suffer from high error rates and a difficulty in scaling qubit counts. Consequently, it is difficult to predict when universal quantum computers will scale to their full potential. In Figure 2, Dr. Yaakov Weinstein from the MITRE Corporation illustrated the range of scaling predictions using the concept of Quantum Volume (i.e., the minimum of either number of qubits or number of successful qubit operations implemented before an error occurs). The horizontal dashed lines in the figure benchmark quantum volume against some well-known quantum algorithms.

Within the United States, competing technologies from IonQ, Quantinuum, IBM, and Google all predict major advancements by 2030, according to Dr. Weinstein. Outside of the United States, there are major investments in Europe, Australia, Canada, and China. These international quantum computers currently range in qubit counts of tens to hundreds. Along with the United States, both China and Canada have conducted successful quantum supremacy demonstrations; that is to say, they have demonstrated a quantum computation that would not be feasible for a classical computer.

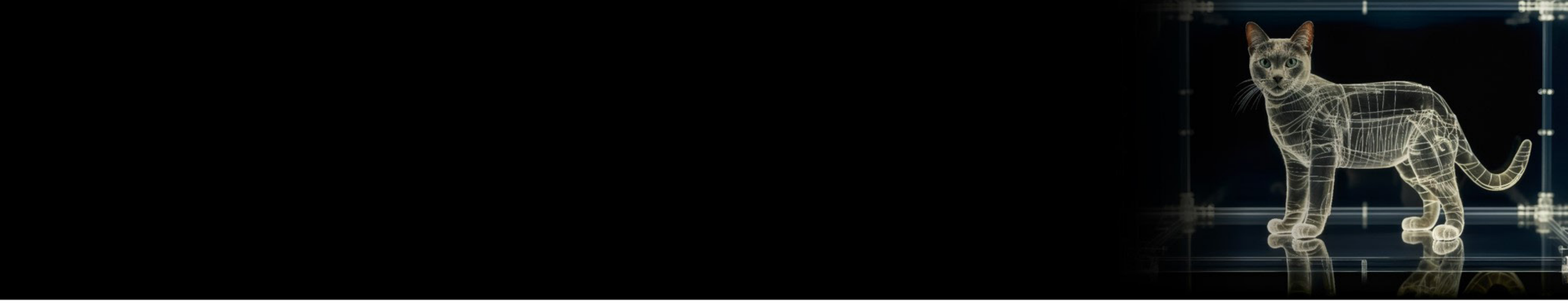
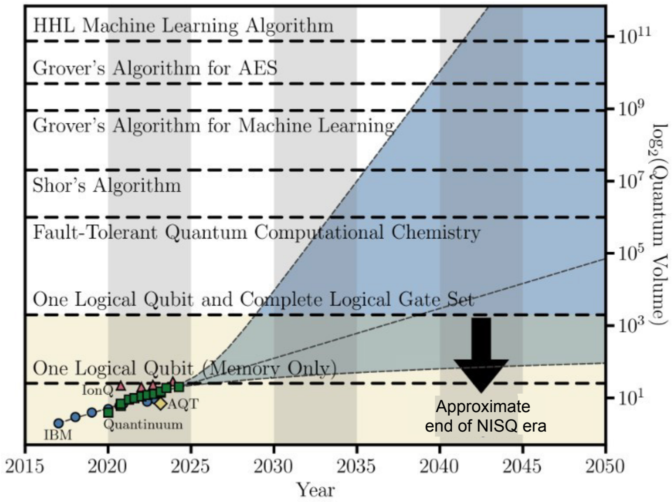
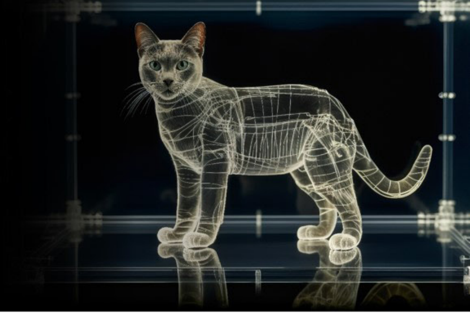


Figure 2. A range of predictions for scaling universal quantum computers. (Source: Y. Weinstein, MITRE Corp.)



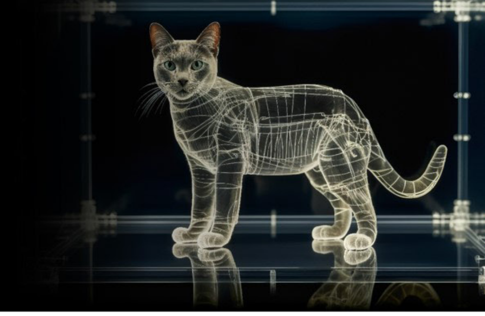
Dr. Klein discussed how certain quantum algorithms, such as those utilizing phase estimation or the quantum Fourier transform, place higher demands on qubit quality and error correction. He expects that intermediate quantum computers will be differentiated for some algorithms running at scale with low precision qubits and others that are restricted to small scale but high precision. Dr. Klein and other panelists noted that both quantum and classical algorithms continue to improve. There are cases where algorithms thought to be purely in the domain of quantum computing have later been shown to have an efficient classical counterpart. (From a transportation perspective, this competition between approaches is good news—we want new methods to solve transportation problems and will take the best of what quantum and classical technology may offer.)

The panel discussed development tools that are available today and discussed the steps required to mature software in the future. Open-source tools like Qiskit for gate-based computing are in use and evolving to serve the role that languages like Python or C++ serve for classical computers. D-Wave provides a Python SDK for access to their annealing quantum computers. Dr. Klein expects that compliers—that is, the software that converts code to a sequence of qubit interactions—will be fully mature (i.e., portable, efficient) in 5 to 10 years.



Further Reading on Quantum Computing

1. Committee on Science of the National Science & Technology Council. 2018. *National Strategic Overview for Quantum Information Science*. Last accessed 10/30/24: https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf.
2. Quantum Economic Development Consortium (QED-C). Quantum Computing for Transportation and Logistics. Arlington, VA: March 2024. https://quantumconsortium.org/mp-files/quantum-computing-for-transportation-and-logistics-2024.pdf/.
3. Bush, S., Y. Duan, B. Gilbert, A. Hussey, J. Levy, D. Miller, R. Pooser, M. Syamlal. 2020. *Fossil Energy Workshop on Quantum Information Science & Technology Summary Report*. U.S. Department of Energy, National Energy Technology Laboratory: Pittsburgh, PA. Last accessed 10/30/24: https://netl.doe.gov/sites/default/files/2020-07/QIST%20Workshop%20Summary%20Report_Final_20200730.pdf.
4. Nielsen, M. A., and I. L. Chuang. 2010. Quantum computation and quantum information. Cambridge University Press.
5. IBM Institute for Business Value. 2024. The Quantum Decade. Last accessed 10/30/24: https://www.ibm.com/thought-leadership/institute-business-value/en-us/report/quantum-decade.
6. D-Wave. 2022. *SavantX: Logistics Optimization at the Port of Los Angeles*. Last accessed 10/30/24: https://www.dwavesys.com/media/y3hl22va/dwave_port_of_la_case_story_v7.pdf.



Quantum Sensing

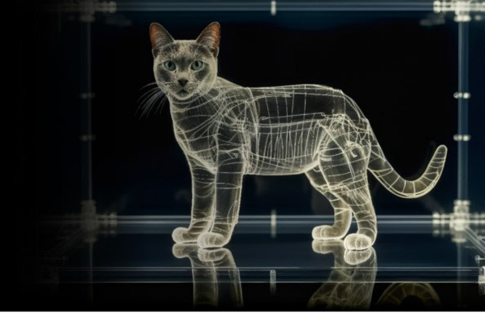
The advantages of quantum sensors over their classical counterparts include higher sensitivity; increased long-term stability and accuracy; the ability to self-calibrate; and reduced size, weight, and power. Quantum sensors are commercially available or are rapidly maturing for use in communications, finance, medicine, resource exploration, and chemical detection. The purpose of this section is to explore the benefits of quantum sensing in transportation.

What Is a Quantum Sensor?

Quantum sensors exploit the same properties of atoms, photons, and superconductors that enable quantum computing, except in quantum sensing, the fragility of quantum states due to interactions with the external environment are turned from a weakness to a strength. During the preworkshop webinar, MIT Professor Dr. Paola Cappellaro drew a distinction between this and more familiar technologies that make use of quantum objects but exploit the object in a classical way. For instance, MRI uses the uniquely quantum quantity of spin, but exploiting this signal only requires a classical understanding of magnetism. Dr. Cappellaro contrasted this with the quantum advantage that is gained through exploiting the wave properties of matter, including coherence, superposition, and entanglement. As an example, spatial interferometers split atom waves via superposition; these waves are allowed to evolve in the presence of an external influence (e.g., magnetic fields, acceleration) and are then recombined and measured in a process known as interference. Furthermore, the sensitivity of the measurement is enhanced if the atom waves are entangled by essentially creating larger waves that evolve together rather than individual smaller ones.

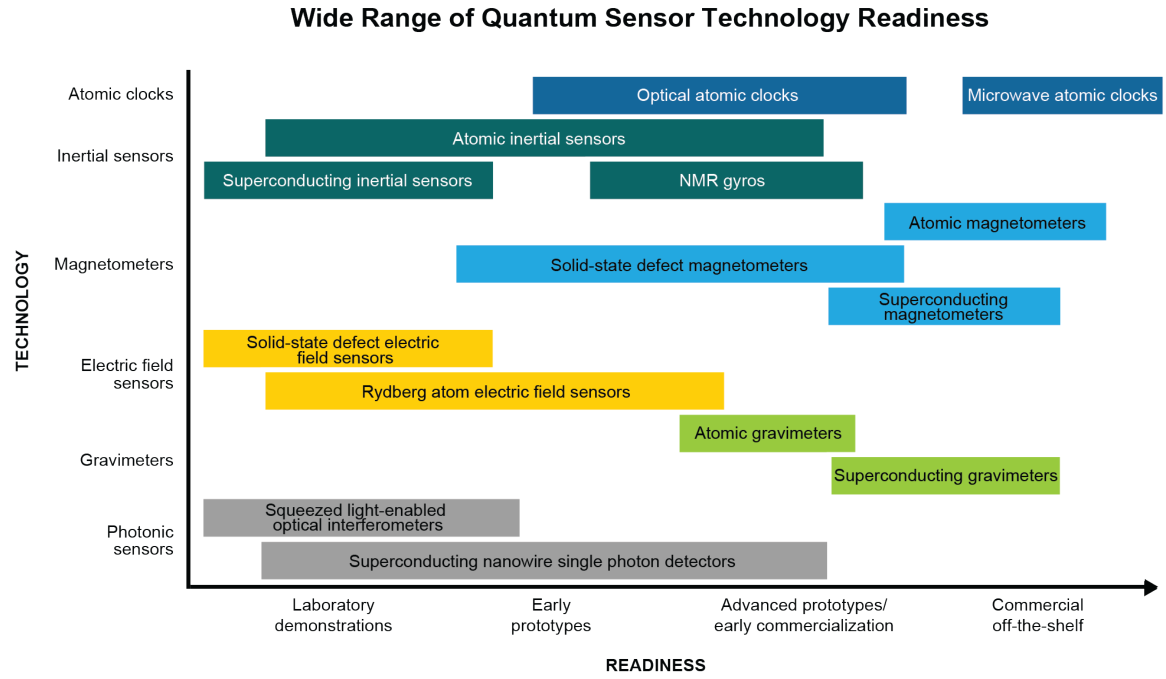
Dr. Bonnie Marlow of the MITRE Corporation described the landscape of quantum sensing technologies. Depending on the application, the advantages of quantum sensors over their classical counterparts include higher sensitivity; increased long-term stability and accuracy; the ability to self-calibrate; and reduced size, weight, and power. Atomic clocks are the oldest and most familiar example of quantum sensors, and this technology continues to improve—becoming smaller, cheaper, and more stable. These clocks serve as the basis for our national time standards terrestrially and in space. Quantum sensors are also mature or are maturing for use in communications, medicine, resource exploration, chemical detection, and particularly in each of the constituent capabilities included in PNT.

Figure 3 contains a survey of methods in quantum sensing, categorized by type and arranged according to maturity. In addition to the interferometer example, other quantum sensing techniques involve interactions with highly excited states of electrons in an atom gas (Rydberg atoms) or on the orientation of atomic nuclei (nuclear magnetic resonance). Still, other classes of sensors involve quantum properties that emerge from an ensemble of atoms working together, which is the case for crystal structures engineered with impurities (solid state defect sensors) or in superconductivity where electrons move freely among certain types of cooled atoms without



resistance. A final class of quantum sensor uses photons in squeezed or entangled states to beat the noise limits of classical/semiclassical sensors, such as lidars, laser-based spectrometers, and radars.

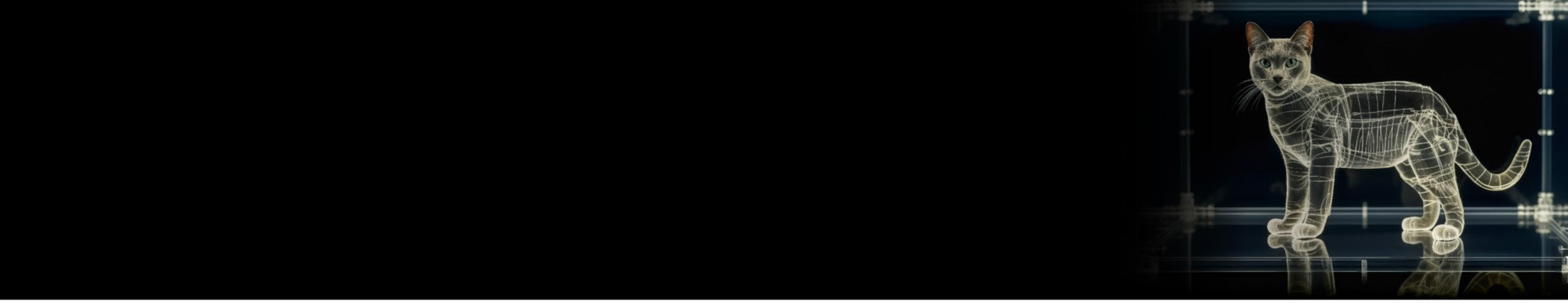
Figure 3. Maturity of quantum sensors. (Source: B. Marlow, MITRE)



How Are Quantum Sensors Used Today?

Commercially available quantum sensors include clocks, magnetometers, and gravimeters. Microwave atomic clocks range from low-cost chip-scale devices to high-end hydrogen maser clocks. A key application of these clocks is to provide time holdover—that is, the ability for a system to maintain time synchronization when an external reference like GPS is lost or not trustworthy. These time references are integrated into critical infrastructure like power grids and telecommunications and for timestamping financial transactions. According to Dr. Max Perez, Vice President at Infleqtion, high precision optical atomic clocks with days or weeks of holdover will soon be on the market for defense and commercial applications (e.g., data centers, communications networks) for a few hundred thousand dollars each.

Magnetometers and gravimeters have been demonstrated as alternatives to GPS for positioning, providing an advantage over classical sensors in terms of long-term stability and accuracy. Position is inferred through a process of comparing local variations in gravitational or magnetic fields to maps of naturally occurring anomalies. Gravimeters are also used for detecting underground tunnels, studying volcanoes, and mineral exploration. Magnetometers are used



in medical applications, including heart and brain monitoring and microelectronics assurance, and for radio frequency applications, including communications and remote sensing. Atomic inertial sensors built around the interferometer concept described in Section III have also been demonstrated.

How Might Quantum Sensors Change the Way USDOT Works In the Future?

Table 2 summarizes the quantum sensing opportunities that were identified during the workshop and maps each to transportation modes where benefits may accrue. This modal matrix can be used to identify opportunities for USDOT OAs to coalesce around these topics, as will be discussed in Section IV.

Table 2. Opportunities for quantum sensing in transportation.

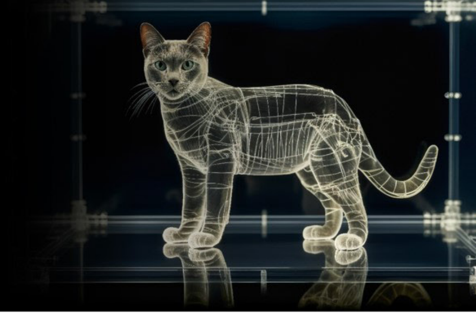
	Transportation Mode								
Quantum Opportunity	**Vulnerable Road Users**	**Passenger Vehicles**	**Rail**	**Trucking**	**Public Transit**	**Aviation**	**Infrastructure**	**Maritime & Seaway**	**Pipeline / Hazardous Materials**
Infrastructure Resilience	●	○	●	○	○	○	●	●	●
Corrosion/Leak Detection	○	○	●	●	○	●	●	●	●
Communications	●	●	●	●	●	●	●	●	○
Navigation	●	●	○	●	●	●	○	●	
Time Synchronization	○	●	●	●	●	●	●	●	●
Underground/ Underwater Surveys	○	○	○	○	○	●	●	●	○
GHG Emission Monitoring	○	●	●	●	●	●	○	●	●

● = identified opportunity; ○ = not applicable or unknown.

These opportunities are also readily organized by the goals defined in the USDOT RD&T Strategic Plan. Like in the discussion of quantum computing, we focus on safety, economic strength and global competitiveness, equity, and climate and sustainability. In the subsections that follow, the applications listed in Table 2 are placed in context by strategic goal along with a brief explanation of how the technology has the potential to transform transportation.

Safety

Quantum sensing supports the USDOT's strategic goal of building safer infrastructure, vehicles, and systems enabling all modes of transportation. Workshop participants identified opportunities in PNT, pipeline safety, and communications as future applications for quantum sensing. Quantum sensors for PNT are already achieving high technology readiness levels.



Quantum technologies offer inertial, magnetic, and gravitational anomaly-aided navigation as alternatives when space-based signals are unavailable or unreliable. The consensus among workshop panelists is that magnetic anomaly-aided navigation is most appropriate for aircraft and gravity-based navigation is most appropriate for maritime applications. Long holdover clocks will be essential for ensuring the safety of navigation and communications systems during periods when terrestrial or space-based time synchronization signals are lost, jammed, or spoofed.

The RD&T Strategic Plan also identifies the need to protect communities from transportation risks posed by hazardous materials. Pipeline, rail, and truck applications all require leak and corrosion detection for identifying dangerous or explosive scenarios quickly and at low concentrations. Spectrometers that employ entangled laser illumination will be more sensitive in these scenarios than their modern counterparts.

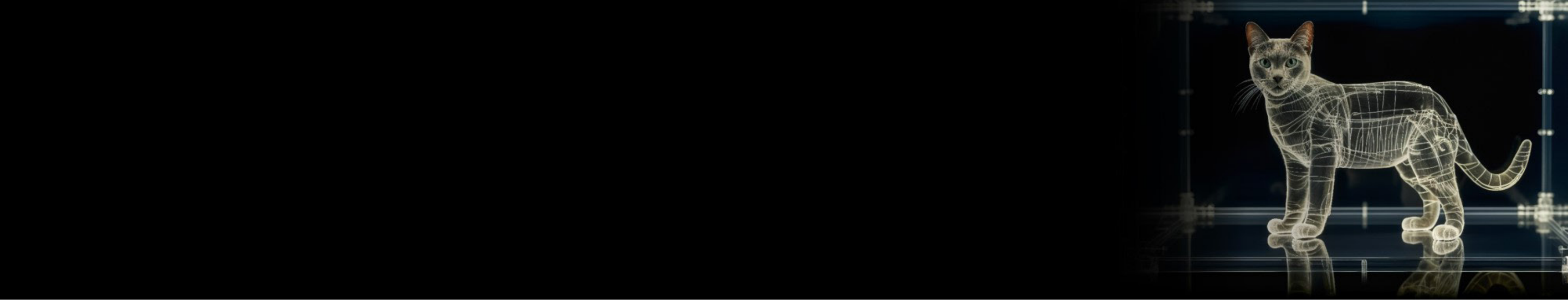
Modern vehicles bristle with radars and radios. Dr. Vengalattore discussed the potential for Rydberg atom sensors in communications systems and in radio frequency applications more generally. Coin-sized Rydberg atom sensors may enable combined communications and sensing systems that are truly software defined, including at the aperture in addition to backend processing. The upshot will be safety critical sensing and communications plus the ability to implement entirely new modes via software updates, all in a small hardware package.

Economic Strength and Global Competitiveness

Economic strength and global competitiveness are built upon reliable and resilient infrastructure. Workshop participants identified infrastructure planning and monitoring as potential applications for quantum sensors. On land, infrastructure monitoring applications could include integrated quantum sensors for temperature, pressure/strain, corrosion, and other variables that require long-term stability and the assurance of self-calibration. These monitoring applications could manifest as entirely new sensors or enhancements to existing sensors, like entanglement-enhanced fiber sensing. During planning, infrastructure surveys may benefit from gravimetry for observation of large but hard-to-observe underground cavities, water, and other features. In maritime/seaway applications, workshop participants considered potential benefits from integrated quantum sensors and applications for gravimetry-enabled bathymetry.

Equity

Workshop participants did not find opportunities for quantum sensing to directly address disparities in transportation equity. Quantum technologies can provide new opportunities for wealth creation by establishing quantum incubators for solving transportation problems in partnership with disadvantaged small businesses or with universities that could educate and train underserved students for entry into a highly skilled quantum workforce.



Climate and Sustainability

Dr. Ruishu Wright from DOE's National Energy Technology Laboratory discussed opportunities for quantum sensors in methane-leak detection and in-pipe gas composition monitoring. The U.S. Environmental Protection Agency estimates that methane accounts for 12 percent of all U.S. greenhouse gas emissions, with an impact that is 28 times greater than carbon dioxide in terms of trapping radiation in the atmosphere.[3] Quantum-enhanced fiber sensors can be used to increase sensitivity and resolution while retaining the fiber's ability to sense over extremely long lengths of pipeline. Dr. Wright envisions new ways to detect leaks early over vast distances, protecting the public from pollutants and climate damage.

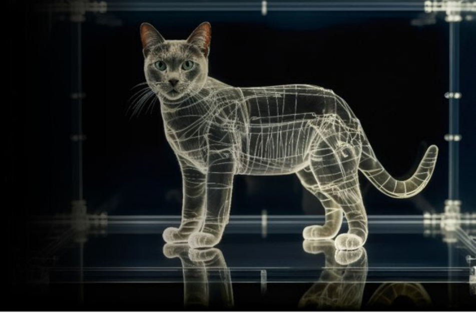
When Might USDOT Need to Be Ready?

Several quantum sensing technologies discussed by the workshop keynote speakers and panelists are at or near commercial maturity. Nuclear magnetic resonance (NMR) inertial sensors already have a form factor like classical sensors but with better performance. Atom interferometers are being miniaturized now. The speakers and panelists emphasized that real-world performance outside the laboratory involves compromises. Furthermore, we should expect classical sensors to continue to improve and, in some cases, outperform quantum sensors outside of the laboratory. The consensus was that the primary remaining challenges are in systems engineering and design and in improving classical enabling technologies like microelectronics rather than in quantum physics. The furthest prediction for commercial readiness was 10 years for quantum-enhanced sensing of pipeline applications.

Dr. Perez expects his company will have commercially available optical atomic clocks in 6 months and quantum radio frequency sensors in 18 months. This optical clock will initially cost several hundred thousand dollars, but he predicts the price will decrease over time. Dr. Perez states that Infleqtion is also developing a PNT suite for aircraft and ships that will be entering a demonstration phase in 2025.

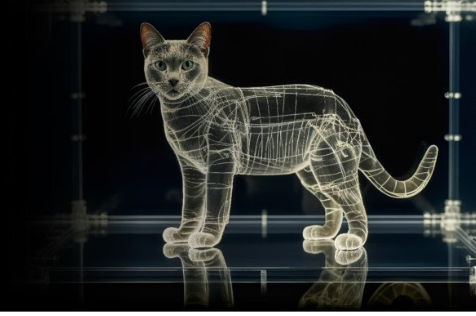
Workshop participants from the Department of Defense (DOD) are investing in classical and quantum sensors for PNT so that they will have multiple inertial and map-based alternatives if GPS is jammed, spoofed, or incapacitated. Dr. Vengalattore emphasized DARPA's role in miniaturization of these technologies. Dr. Michael Slocum from the Air Force Research Laboratory expects quantum inertial navigation and magnetic anomaly navigation technology will be ready to replace classical systems in the next 3 to 5 years. In the case of magnetic navigation, this timeline creates a near-term demand for magnetic anomaly maps along air travel corridors. Mapping is predicted to cost $70 per linear kilometer. Dr. Slocum expects quantum magnetometers to drop in price from $50,000 now to around $5,000 in approximately 5 years.

3 U.S. Environmental Protection Agency. 2024. "Overview of Greenhouse Gases" [website]. Last accessed 10/30/24: https://www.epa.gov/ghgemissions/overview-greenhouse-gases.



Further Reading on Quantum Sensing

1. Quantum Economic Development Consortium (QED-C). 2022. *Quantum Sensing Use Cases*. Last accessed 10/30/24: https://quantumconsortium.org/mp-files/quantum-sensing-report-2022-revised-11-18-22.pdf/.
2. Cassel, R., W. Tobias, and B. Marlow. 2023. *Quantum vs. Classical Complementary PNT*. Last accessed 10/30/24: https://www.mitre.org/sites/default/files/2024-06/PR-23-0577-Quantum-vs-Classical-Complementary-PNT.pdf.
3. Bush, S., Y. Duan, B. Gilbert, A. Hussey, J. Levy, D. Miller, R. Pooser, and M. Syamlal. 2020. *Fossil Energy Workshop on Quantum Information Science & Technology Summary Report*; U.S. Department of Energy, National Energy Technology Laboratory: Pittsburgh, PA. Last accessed 10/30/24: https://netl.doe.gov/sites/default/files/2020-07/QIST%20Workshop%20Summary%20Report_Final_20200730.pdf.



Next Steps

USDOT can efficiently leverage advancements in quantum technologies without sacrificing attention to near-term needs. We can be ready when our Nation experiences a quantum watershed moment, like for artificial intelligence in 2023, with a small cadre of transportation domain experts cross-trained in quantum technologies; a limited investment in foundational projects; and a large, established network of quantum experts across government, industry, and academia, domestically and internationally. The purpose of this section is to define six arenas in which USDOT may make positive first steps.

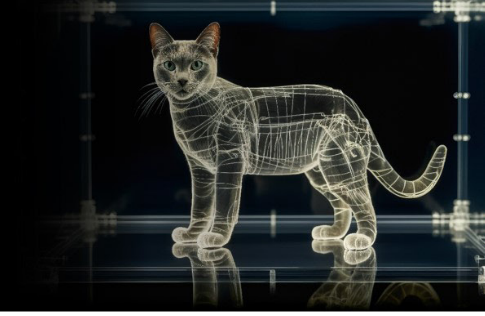
Policy

The 2018 National Quantum Initiative Act establishes “a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.”[4] The act is implemented through the National Science and Technology Council’s Subcommittee on Quantum Information Science (SCQIS) to build a quantum-smart and diverse workforce, encourage industry engagement, provide necessary infrastructure, drive economic growth, maintain national security, and foster international collaboration in the field of quantum information science. USDOT has the opportunity to join the Departments of State, Energy, Commerce, and Defense, along with other federal partners on the SCQIS, to bring the benefits of coordinated federal research into the USDOT OAs and to contribute to the subcommittee’s work though the development of transportation applications and use cases.

Regulation and Standards

Safety-related applications were featured prominently for quantum computing (Section II) and quantum sensing (Section III). The six USDOT OAs with safety-related regulatory responsibilities could team to develop a quantum technology assessment framework to anticipate vulnerabilities and identify in-house research questions that support the development of future regulations. This process could begin by building upon the technology landscape surveyed during this workshop to evaluate whether current rules require alteration. For instance, what regulations would apply in the air, on the surface, or on the water when a Rydberg atom sensor is used simultaneously as an antenna for GPS, radar, and communications signals? How will maps for gravity and magnetic field navigation be assessed for safe navigation? Similarly, this team could develop a process for identifying quantum gaps in voluntary standards and encourage participation from the salient professional societies.

4 National Quantum Coordination Office. 2024. "National Quantum Initiative" [website]. Last accessed 10/30/24: https://www.quantum.gov.



Planning and Economic Development

USDOT OAs play a central role in developing and maintaining state and local transportation networks. These activities span funding, planning, building, and operations. Questions of where and how federal resources can make the most impact are well suited for quantum optimization, including economic impact, equity, climate, and sustainability. The use of quantum computers for optimally distributing EV charging stations and quantum machine learning for flash flood prediction (Section II) are examples of how this works today. The OAs could team up to develop other use cases in this spirit that can be demonstrated on quantum or quantum-hybrid computers at smaller scales now and large scales in the future. High-priority use cases can turn into funded projects with industry, universities, and other government partners.

Enforcement and Inspections

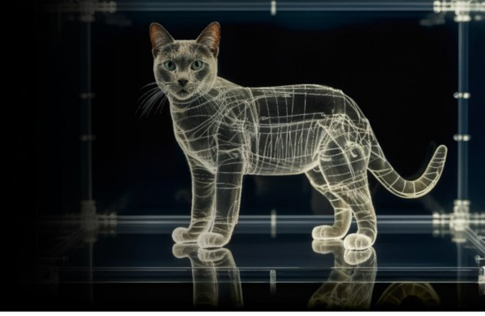
USDOT OAs with enforcement and inspection responsibilities can reduce uncertainty, encourage quantum innovation in the transportation sector, and set expectations for the quantum industry by publishing guidance on how and when these emerging technologies intersect with existing enforcement authorities. The *National Highway Traffic Safety Administration (NHTSA) Enforcement Guidance Bulletin 2016-02: Safety-Related Defects and Automated Safety Technologies*[5] is an excellent example of how this may be achieved. NHTSA's guidance appeared more than 2 years before the first commercial robotaxi service in the United States. We are within a similar timescale for quantum sensing in transportation applications and possibly not much further out from the widespread use of quantum computing.

There is also an opportunity to employ quantum computing and sensors directly in road, rail, pipeline, and other inspections within the purview of USDOT. As discussed in Section III, infrastructure and pipeline monitoring applications could include integrated quantum sensors for temperature, pressure/strain, corrosion, and other variables that require long-term stability and the assurance of self-calibration. Quantum sensors can also be applied to problems in underground and underwater mapping. Quantum computers can be used to better predict chemical and dynamic processes, such as corrosion or fluid dynamics that degrade bridges, rails, ships, planes, and hazmat containers, leading to better use of inspection resources.

Research

The quantum computing experts that participated in our webinar and workshop have been unanimous in their request to team up with USDOT on use cases and algorithm development. These teams can decompose concepts into components that leverage quantum advantage and then evaluate performance on the NISQ and annealing quantum computers of today to be ready

5 National Highway Traffic Safety Administration. 2016. *NHTSA Enforcement Guidance Bulletin 2016-02: Safety-Related Defects and Automated Safety Technologies*. Last accessed 10/30/24: https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/final_enforcement_guidance_bulletin.pdf.



for the universal quantum computers of tomorrow. The key benefit in any near-term demonstration is in developing institutional understanding of how quantum parallelism applies to transportation problems—a small investment now may prevent poor investment decisions in the future.

USDOT can utilize quantum computers now for investigating topics from artificial intelligence to computational fluid dynamics. The Quantum Computing User Program (QCUP) at Oak Ridge National Laboratory (ONRL) was introduced by Dr. Phil Lotshaw. Through this program, ONRL provides access to the best available computing resources for participants to implement and test quantum algorithms. The specific goal of the QCUP is to grow the quantum information science ecosystem through partnerships with universities, government, and industry.

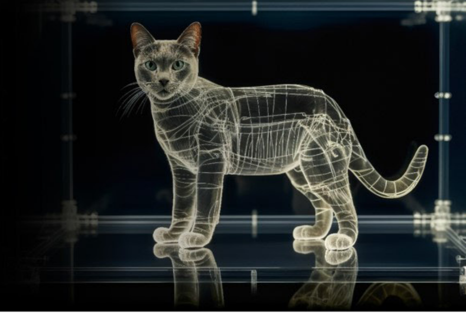
Quantum sensing offers a variety of opportunities for near-term experimentation with multimodal impact. USDOT could partner with DOD on evaluating magnetic anomaly-based navigation, gravitational anomaly-based navigation, quantum inertial navigation, and the utility of distributed atomic clocks on resilience for automation, critical infrastructure, and communications. Likewise, quantum gravimeters can be evaluated for underground and underwater surveys while quantum magnetometers, temperature, and pressure sensors can be evaluated for pipeline, rail, and bridge health monitoring.

The knowledge gained through research and experimentation should be curated and shared via a transportation use case knowledge base for capturing our collective experiences with quantum technologies within USDOT. We should also collect and publish metrics and benchmarks for matching quantum sensing concepts with operational requirements in transportation. Section V provides a snapshot of near-term research and demonstration opportunities for quantum computing and quantum sensing.

Outreach and Partnerships

USDOT can maintain a healthy dialogue with the quantum community using the same tools we use to communicate with the transportation research community. Examples include one-way formal communications, such as the Annual Modal Research Plans, or formal exchanges on more narrowly defined topics via Requests for Information. Such efforts can also include bringing a transportation voice to quantum workshops and conferences while also recruiting quantum participants for transportation-focused gatherings.

We can also establish direct, recurring dialogue and partnerships on individual projects with other government agencies that have mutually reinforcing missions and are major investors/innovators in this technology area. Workshop participants from DARPA, DOD labs, and DOE labs all expressed a willingness to collaborate with USDOT. Another national resource in this technology area is the National Institute of Standards and Technology. Finally, analogous nonfederal partnerships can be developed via Cooperative Research and Development Agreements in which both parties may share resources (e.g., personnel, equipment, and intellectual property, but not federal funding) for advancing synergistic goals.



Near-Term Research and Demonstrations

This section provides examples of key quantum technology programs that USDOT can start now and complete in 12 to 36 months (i.e., modest investments with large future impacts).

Network Optimization

Concept: Integrate quantum optimizers with existing digital twins in a multimodal transportation network to minimize overall passenger or cargo transit time and fuel consumption.

Anticipated Benefits: Better use of existing resources—less time in traffic and increased fuel efficiency as well as increased opportunities for work and education in urban and rural communities. Plan new road construction where it is economically beneficial while conserving our neighborhoods and natural spaces.

Machine Learning for Safety and Maintenance

Concept: Leverage quantum machine learning's ability to find patterns in complex and chaotic signals to provide early warnings for safety and maintenance issues in sensor data and communications signals across all modes of transportation and levels of automation.

Anticipated Benefits: Fewer accidents, fewer injuries, and higher reliability.

Computational Fluid Dynamics

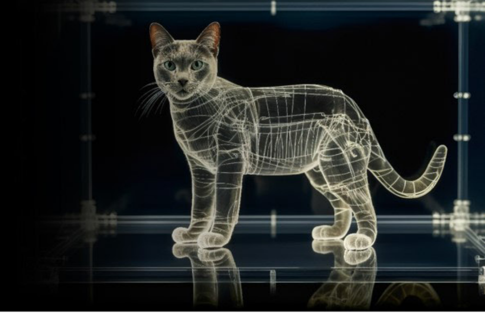
Concept: Translate advances in quantum linear algebra methods to solve the partial differential equations that are the foundation for problems like bridge scour and erosion and in the fuel-efficient design of ships, aircraft, and surface vehicles.

Anticipated Benefits: Longer lasting bridges and vehicles that are more efficient on ground, at sea, and in the air, saving money and reducing emissions.

Time Synchronization and Holdover

Concept: Deploy lower-cost atomic clocks for assured, tamper-proof synchronization of safety critical communications systems and navigation with long holdover when GPS is denied or unreliable.

Anticipated Benefits: Transportation system resiliency in the face of cyberattacks, terrestrial jamming and spoofing, strategic competition in space, and adverse space weather.



Position and Navigation

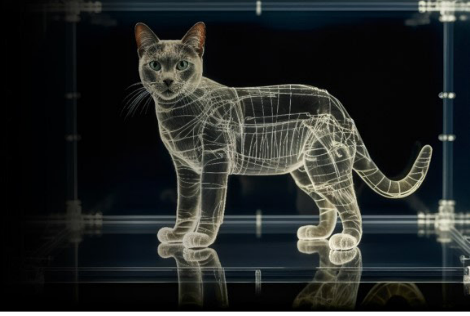
Concept: Evaluate quantum technologies for inertial, magnetic, and gravitational anomaly-aided navigation as alternatives when other navigation aides are unavailable or unreliable.

Anticipated Benefits: Transportation system resiliency in the face of cyberattacks, terrestrial jamming and spoofing, strategic competition in space, and adverse space weather.

Leak Detection

Concept: Test quantum leak and corrosion detection sensors for evaluating dangerous or explosive scenarios quickly and at low concentrations for pipeline, rail, and truck applications involving the transport of hazardous materials.

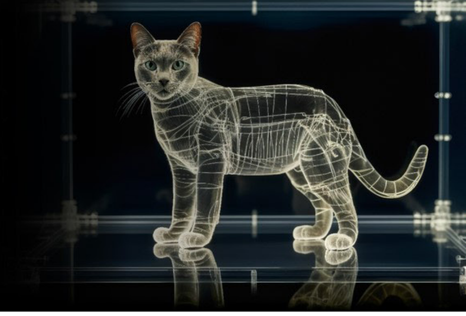
Anticipated Benefits: Protection against the risks to people, property, and the environment that are a consequence of transporting hazardous materials.



Appendix A

Table 3. Workshop registration by USDOT OA.

Operating Administration	Percent of Representation
Federal Highway Administration	26.8
Federal Aviation Administration	20.5
Office of the Secretary of Transportation	15.7
National Highway Traffic Safety Administration	11.0
Volpe National Transportation Systems Center	9.4
Pipeline and Hazardous Materials Safety Administration	7.9
Federal Motor Carrier Safety Administration	3.1
Maritime Administration	3.1
Federal Transit Administration	2.4



Appendix B

Workshop Agenda

Quantum Technologies in Transportation Workshop
U.S. Department of Transportation
July 10, 2024 (Wednesday)

8:30 am - 8:40 am ET

Welcome Remarks
- Cordell Schachter Chief Information Officer, U.S. Department of Transportation
- Gretchen Campbell, Deputy Director of the National Quantum Coordination Office

8:40 am - 8:45 am ET

HASS COE, ARPA-I: Overview of agenda and day

8:45 am - 9:00 am ET

Keynote 1: How to be a Savvy Quantum Consumer
Dr. Mukund Vengalattore, Program Manager, Defense Advanced Research Projects Agency

9:00 am - 9:15 am ET

Keynote 2: How Quantum Technologies Can Revolutionize Transportation
Rob Hovsapian, Research Advisor, National Renewable Energy Laboratory

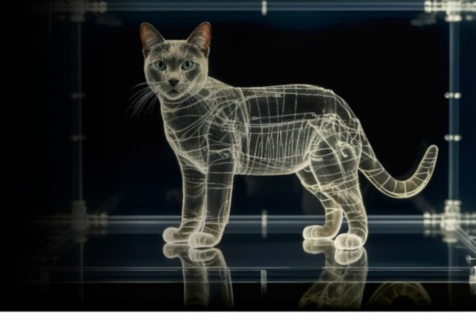
Transition to Quantum Computing Panel

9:15 am - 10:15 am ET

Introduction to Quantum Computing
Speakers:
- Yaakov Weinstein, Chief Scientist for Quantum Technologies, MITRE (Moderator)
- Thomas Ward, Quantum Industry Application Consultant, IBM
- Phil Lotshaw, Research Scientist, Computational Sciences and Engineering Division, Oak Ridge National Laboratory
- Franz Klein, Founding Director, National Quantum Laboratory, Q-Lab
- Allison Schwartz, Global Government Relations & Public Affairs Leader, D-Wave

Break

Transition to Quantum Sensing Panel



10:30 am - 11:30 am ET

Introduction to Quantum Sensing
Speakers:
• Bonnie Marlow, Principal Physicist, Quantum Sensors Group Leader, MITRE (Moderator)
• Michael Slocum, Research Electronics Engineer, Air Force Research Laboratory
• Ruishu Wright, Research Physical Scientist, National Energy Technology Laboratory
• Max Perez, Vice President, Infleqtion

Transition to Quantum Key Glossary

11:30 am - 12:00 pm ET

Quantum Key Glossary

11:30 am – 11:40 am ET
Alan Chachich, Electronics Engineer, Volpe National Transportation Systems Center

11:40 am – 12:00 pm ET
Audience-led questions | Jonathan Felbinger, Deputy Director, Quantum Economic Development Consortium

12:00 pm - 12:45 pm ET

Lunch Break

All speakers, panelists, and attendees join roundtables.

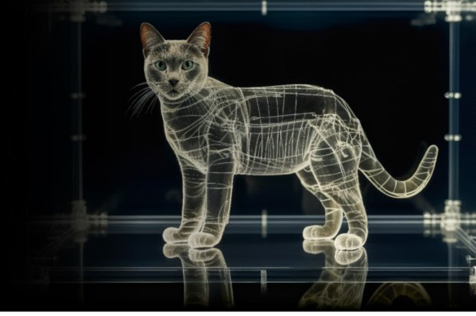
1:00 pm - 2:00 pm ET

Breakout 1: Transportation Industry’s Most Likely Quantum Advantage Areas

Break

2:15 pm - 3:30 pm ET

Breakout 2: If It Works, Will It Matter?
What are the performance requirements and pathways needed for quantum to add value to DOT-specific use cases?



Disclaimers

The views and opinions expressed in this document are the authors and do not necessarily reflect those of the U.S. Department of Transportation (USDOT). The contents do not necessarily reflect the official policy of the USDOT. The U.S. Government does not endorse products, manufacturers, or outside entities. Trademarks, names, or logos appear here only because they are considered essential to the objective of the presentation. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Acknowledgements

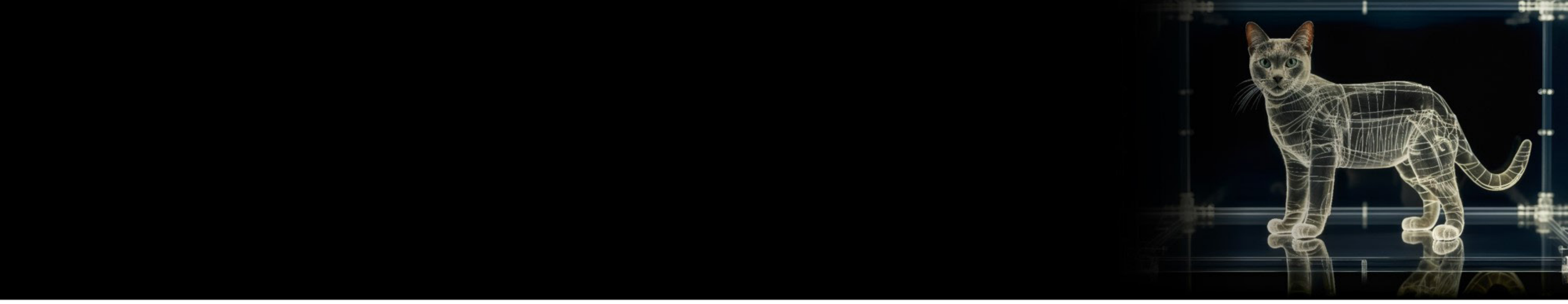
We would like to thank everyone that attended the workshop in person and online. We would like to extend a special thanks to the participants in the afternoon roundtable session for their active contributions to a highly productive ideation session. Table facilitators are indicated in bold.

Workshop Breakout Tables

1. *AI/ML*: Philip Lotshaw, Allison Schwartz, **Yaakov Weinstein**
2. *Optimization*: **Jameson Albers**, Alan Chachich, Rob Hovsapian, Rima Oueid, Kortny Rolston-Duce, Mina Sartipi, Steven Summer
3. *Secure Communications and Optimization*: Jonathan Felbinger, **Franz Klein**, Greg Muhler, Craig Thor, Yan Zhang
4. *Quantum Sensors*: Jonathan Kwoler, Matthew Noor, Erica Wiener, **Ruishu Wright**, Wei Zhang
5. *PNT*: Bill Barfield, Rodrigo Castillo-Garza, David Kuehn, **Bonnie Marlow**, Max Perez, Suzanne Sloan, Mike Slocum
6. *Simulation*: Rich Davies, John Farrell, Abeynaya Gnanasekaran, John Hourdos, **Robert Ledoux**, Amit Surana, Stephen Zoepf
7. *AI/ML*: Jamir Cavar, Adian Cook, Felix Delgado, James Pol, **Thomas Ward**, Ross Wong

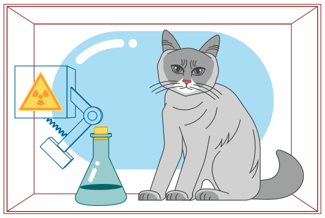
Workshop Virtual Tables

1. *AI/ML*: Jennifer Aponte Rivera, Stephen Arnold, Mohamadreza Banihashemi, Neil Chaudhry, Vincent Domen, Jeffrey Dressel, Ana Eigen, Chris Evans, Walton Fehr, Volker Fessmann, **Ed Heinbockel**, David Jackson, **Jason JonMichael**, **Andrew McClung**, Derek Morgan, Khang Nguyen, Marilyn Rivera, Jake Sagha, Abhijit Sarkar, Steve Sill, Calvin Tang, Peter Wu
2. *Sensors*: Akinlolu Akinmboni, Danielle Chou, Gabriela Vallejo, Gary Lander, Gunyoung Lee, Erik Priest, Lauren Redd, **Brent Young**



We would also like to thank our volunteer reviewers for their suggestions and improvements to this paper, including Alan Chachich, Jason JonMichael, David Kuehn, James Pol, Allison Schwartz, Ronald Stroup, Yaakov Weinstein, and Thomas Ward. Their contributions have improved our product, but responsibility for mistakes or omissions belongs with us. Their willingness to provide feedback should not be interpreted as endorsement of any individual view or opinion expressed in this paper.

Why the Cat?



Schrödinger's cat is a thought experiment that implies that reality at the quantum level is inherently probabilistic and dependent on observation.

Schrödinger's cat is a reminder of how unlike the quantum world is from our everyday experience. Join us as we build the world's leading transportation system upon this frontier of science.

Contact

Authors

Daniel A. LeMaster, Ph.D.
Senior Scientist, HASS COE
daniel.lemaster@dot.gov

Prachi Vakharia
Strategic Advisor, ARPA-I
prachi.vakharia.ctr@dot.gov

Communications

Denise Bakar
Manager, HASS COE
denise.bakar@dot.gov

Learn More

www.transportation.gov/hasscoe/highlights/quantum