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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1090

Risks Related to Emerging and Disruptive Transportation Technologies

A GUIDE

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2024

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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This report was prepared under NCHRP Project 23-15, "Guidance on Risks Related to Emerging and Disruptive Transportation Technologies." It provides insight into the difficult problem of risk management for transportation agencies in the face of emerging and disruptive technological change. It presents a risk register for various potential sources of risk in the realms of electric vehicles, connected autonomous vehicles, mobility on demand/mobility as a service, and advanced air mobility. Most importantly, it lays out guidelines for how estimations of risk and the associated consequences may be continuously updated and compared by agency risk managers in the face of dynamic change.

RAND Corporation (RAND) served as the prime contractor. Steven W. Popper of Tecnológico de Monterrey (formerly with RAND), served as the principal investigator. The RAND project team included Fabian Villalobos, Hye Min Park, Jalal Awan (currently with The Utility Reform Network), and Zara Abdurahaman.

Sam Schwartz served as the principal subcontractor. Sam Schwartz staff partnered with RAND on all aspects of the project that produced this report. Sam Schwartz team members included Joe Iacobucci and Sydney Maves. Adam P. Cohen provided support to Sam Schwartz in the field of advanced air mobility.

Rosa Maria Torres of RAND provided valuable technical assistance in assembling a complicated report.

FOREWORD

By Zuxuan Deng
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NCHRP Research Report 1090: Risks Related to Emerging and Disruptive Transportation Technologies: A Guide develops a register of risks to state and local transportation agencies and their constituents posed by four emerging technologies: electric vehicles (EVs), connected autonomous vehicles (CAVs), mobility on demand/mobility as a service (MOD/MaaS), and advanced air mobility (AAM). The report presents approaches agencies can use to prioritize risks and identifies policies and actions to address risks along with the potential impacts of those policies and actions. The material in this report will be of immediate interest to public agency staff who may deal directly or indirectly with any risks related to emerging and disruptive transportation technologies to the public (e.g., safety, privacy, security, inclusion, equity, mobility, public health, and acceptance) and to agencies (e.g., workforce, budget, tort liability, data governance, and changes in mission or role).

Emerging technologies present many potential challenges to state departments of transportation (DOTs) and other agencies that own and manage the existing infrastructure. Significant uncertainty exists about which changes are most likely to occur and where the largest impacts could be, hampering an effective national alignment in policy and approach. While many emerging technologies are of interest, those seen as most critical are EVs and CAVs (and the necessary infrastructure for their operation), MOD/MaaS, and AAM.

Under NCHRP Project 23-15, "Guidance on Risks Related to Emerging and Disruptive Transportation Technologies," the RAND Corporation was asked to develop a guide to assist transportation agencies, DOTs, regional metropolitan planning organizations, and local agencies to attain a more resilient posture to managing risks that arise from introduction and adoption of emerging and disruptive transportation technologies. The study included a literature review on the sources of risk associated with emerging technologies; developed risk matrices that allow agencies to tailor their priorities for sources of risk from the four emerging technologies and across a range of agency goals; summarized higher-level policies or strategies in the form of policy primers for agencies to use for mitigating risk; and presented recommendations for how agencies can operate with greater confidence as they enter an era with multiplying uncertain risks.

The report is accompanied by presentation materials and an implementation plan that identifies opportunities for dissemination and moving research into practice. These materials are available on the National Academies Press website (nap.nationalacademies.org) by searching for *NCHRP Research Report 1090: Risks Related to Emerging and Disruptive Transportation Technologies: A Guide.*

CONTENTS

SUMMARY

Risks Related to Emerging and Disruptive Transportation Technologies: A Guide

Transportation agencies anticipate and manage risk from emerging and disruptive technologies; however, these technologies may also catch agencies by surprise and affect transportation outcomes. Agency planning and policies are also affected by decisions made by the private sector and the public. Because owners and operators control the facilities, transportation agencies cannot entirely control how transportation modes evolve and how this evolution will affect agency goals. This heightens the risk management challenge for a transportation agency.

The inability to fully anticipate technological futures is not a failure of due diligence; it is inherent in the enterprise of innovation. The goal of this report is to assist transportation agencies, state departments of transportation (DOTs), regional metropolitan planning organizations (MPOs), and local agencies with managing risks arising from the introduction and adoption of emerging and disruptive transportation technologies.

The research team addressed three principal tasks:

1. Develop a register of risks to state and local transportation agencies and their constituents posed by emerging technologies.
2. Recommend approaches agencies can use to prioritize those risks.
3. Identify policies and actions to address the risks along with the potential impacts of those policies and actions.

The research focuses on four examples of innovation in transportation: connected autonomous vehicles (CAVs), electric vehicles (EVs), mobility on demand/mobility as a service (MOD/MaaS), and advanced air mobility (AAM). They are referred to in the report as the "four technologies."

What may be at risk if exposure to a hazard occurs and vulnerability to that hazard is present? What are the potential losses or gains faced by transportation agencies? The report focuses on five principal outward-facing agency goals: **equity, safety, environment and sustainability, mobility,** and **security and privacy.** It also touches on **public health** and **public acceptance** of new technology. In addition, agencies define inward-facing goals such as budgetary solvency, reduced tort liability, workforce, data governance, and changes in agency missions and goals as a result of societal change wrought by technology adoption. In the risk register framework, internal agency goals are treated as one collective set of goals.

Risk arises when some underlying source for risk is present or an event occurs that may cause an agency to face risk. Such a hazard, however, may not lead to risk to one or more agency goals. Risk would arise from a hazard depending on the *likelihood* of an event occurring (e.g., the deployment of EVs as luxury vehicles) and some measurable *consequence* for a specific agency goal (e.g., transportation equity). For this project, emerging and disruptive transportation technologies can also present an *opportunity* if they enable an agency to meet its goals better than it currently can. Thus, there is also a risk of a missed opportunity.

Risk registers are catalogs of experience, including what might be at risk, how likely the risk might occur, and what constitutes best practice in mitigating consequences. Risk registers work well for events with inventories of experience. However, misplaced concreteness (overconfidence in what we know or can predict accurately) can lead to surprise and seriously underestimating the level of risk an agency might be exposed to. The velocity of technological change; the interconnections between different technologies, existing systems, and economic and social processes; the complexity and those relationships; and the changing roles of transportation agencies do not permit agencies to achieve and sustain a static posture for risk management. Rather, the best stance that agencies can take is to determine how they can enhance resilience in their organizations and processes. This report is intended to assist them in moving toward such a posture.

The risk register has been designed to be tailored to local conditions and concerns as well as to accommodate regular updates to technologies. The report provides guidelines for how to do so. It also contains a small number of high-level policies or strategies that would enhance the ability of agencies to maintain resilience in the face of shifting risks as well as develop and implement actions that would be robust to the plausible future states of the world implicit in the different trajectories new technologies might follow.

Practical Issues with a Risk Register of Emerging and Disruptive Technologies

For emerging and disruptive technologies prior to their diffusion, likelihood represents a core uncertainty. For this reason, the research developed proxies for likelihood to use in the risk registers rather than attempt to guess at the probability statistics that are lacking. (The method for developing proxies is discussed briefly here and extensively in Appendix C). One purpose likelihoods serve in risk registers is as measures of how concerned to be about a source of risk. This was the main focus in constructing likelihood proxies.

Two approaches reflecting different states of information were developed as proxies for level of concern (LOC) in lieu of an estimate of likelihood. The characteristics-based LOC (CB-LOC) measure is an assessment based on a decomposition of the perceived intrinsic nature of the hazard/technology combination. The signpost indicator LOC (SI-LOC) is based on observation of data on one or more measures chosen to provide early-warning guidance associated with the hazard/technology combination. The report presumes that this SI-LOC measure, which is based on actual data, if available, and based on indicators tuned to local conditions, would be privileged over the CB-LOC measure if the two provide different likelihood proxies.

The report provides a scale for severity of consequences by which each row of the risk register is assessed. It has been calibrated to balance the consequences across the range of goals and is intended to be locally tailored.

As shown in Figure S.1, the severity score appearing in a risk register row is compared to that row's appropriate LOC measure, standing in as a proxy for likelihood. These two measures are then examined in the risk matrix shown on the lower right quadrant of Figure S.1. The resulting cross reference is the risk priority score reflected in the risk register row.

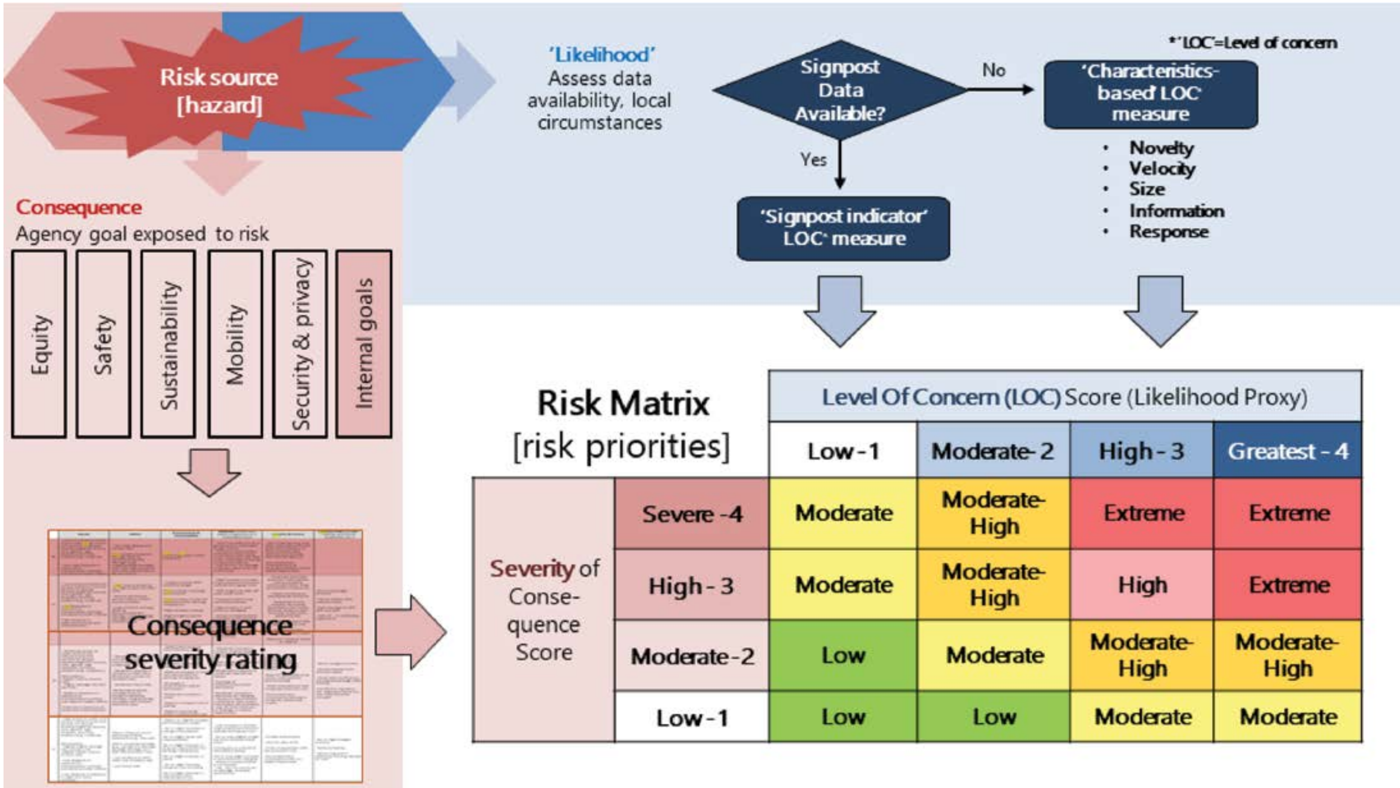

Figure S.1. Diagram of risk priority assessment process.

Differences from Conventional Risk Registers

Chapters 3 through 6 present several enhancements not usually found in more traditional risk registers:

- The risk registers are not intended as static compilations of statistical data. They are intended to serve as a foundation and a framework for adaptation and review by individual transportation agencies.
- Rather than using currently unavailable probability statistics, likelihoods are proxied using two alternative measures. The bases for these assessments are included in the risk registers.
- Severity of consequence is graded in a format that accommodates heterogeneous goals because there are few common denominators among them.
- The concept of signposts is not found in most traditional risk registers.
- All entries are intended to reflect circumstances and risk priority before mitigation.

Policies and Strategies for Agency Resilience to Risks

To better prepare for managing risk arising from emerging and disruptive technologies, agencies will need to (1) position themselves to be organizations resilient to the difficult-to-predict consequences emanating from the adoption of those technologies and (2) develop and implement courses of action designed to be robust to different potential technology pathways. A robust course of action can achieve its intended objectives across a range of possible scenarios.

Examining the mitigating actions that appear across the full risk register leads to a small set of higher-level policies or strategies that agencies could employ to enhance their organizational resilience to change and impart greater robustness to their actions. These strategies are intended to create an organizational consciousness of potential risk that would connect risk management more directly with agency-wide operational and planning activities.

1. **Ensure Access to Necessary Workforce Skills**
   Ensuring access to necessary workforce skills would enhance the agency's ability to manage and mitigate risk related to workforce obsolescence. Emerging technologies may demand a wide-ranging transition of the workforce both internal and external to the agency. This includes creating or eliminating job functions and increasing or reducing the number needed in different job categories.
2. **Monitor for Early Signpost Detection**
   Signposts are early indicators or warnings of a potential hazard, predetermined indicators of a foreseeable hazard that can arise. They are signals of how the future might be trending. As such, they should help agencies as part of a risk management strategy for emerging and disruptive technologies. An organizational awareness of early indicators of emerging risks would bring risk management more directly in contact with routine operational and planning activities.
3. **Enhance Cybersecurity, Data Privacy, and Awareness**
   Emerging and disruptive technologies may blur the lines of categorical risk. The expected connected nature of new transportation modes envisions vehicles interacting with other vehicles, personal mobile devices, transportation infrastructure, and communications and payment networks, creating avenues of attack in the physical and information space. To prepare, agencies need to raise their awareness of measures that could enhance the ability to manage and mitigate risk related to cybersecurity and privacy.
4. **Ensure an Adaptive Culture of Safety to Risks from Emerging Technologies**
   An adaptive culture of safety effectively adjusts and evolves in response to changing circumstances and challenges. It will ensure organizations employ a proactive posture toward addressing new or changing hazards introduced by emerging technology. Safety is not a static goal but a continuous process of improvement that requires ongoing evaluation and adaptation to new risk sources.
5. **Prepare for Data Sharing, Data Management, and Digital Policy**
   The sharing of data among service providers, public agencies, and other key public- and private-sector stakeholders can increase the understanding of the consequences of innovative emerging transportation technologies for travel behavior, equity, and the environment. However, with uncertain standards for data sharing and management, the exchange of data can be onerous and present several security and privacy risks. There is a need to create an organizational consciousness of the potential risk if insufficient attention is given to data-sharing issues.
6. **Detect and Examine Implicit Assumptions to Enhance Awareness**
   An agency's ability to recognize important underlying assumptions that should be made explicit will help to better manage and mitigate risk stemming from the adoption of emerging and disruptive mobility technologies. All plans are forced to make assumptions about the future. Some are explicitly identified. Implicit or unconsidered assumptions can be a source of significant risk management strategy failure. A resilient risk posture includes insight into where hidden assumptions and key assumptions may lie.
7. **Create Capacity for Decision-Making under Deep Uncertainty (DMDU) (Non-predictive) Analytics**
   Means exist to enhance an agency's ability to model, analyze, and plan more effectively despite an increase in transportation system complexity. These methods can allow agencies to explore alternative strategies and policies that are robust (i.e., meet preset

criteria for good outcomes) across a range of possible future scenarios. Transportation agencies produce planning documents using methods based on prediction, but forecasts have become increasingly unreliable. DMDU methods are beginning to be adopted to enhance strategic-level transportation planning.

8. **Strengthen Sensitivity to Equity Implications of Agency Decisions**

   Past transportation decisions have led to inequitable sharing of benefits and burdens across different communities. Agencies will need frameworks, postures, and approaches for building equity into every step of the decision-making process so that all emerging mobility technologies will have equity considerations integrated into each step of decision-making.

9. **Practice Early Stakeholder and Community Engagement**

   Collaborating with stakeholders and community groups to create a shared vision for emerging transportation technologies is critical for risk management. In addition to cross-agency communication and collaboration, there are practical reasons for agencies to engage stakeholders and the public. While environmental processes may be an effective tool for assessing the technical viability of innovative mobility deployments, early stakeholder and community engagement is important to understand and address potential concerns.

Moving Forward Inside State DOTs and MPOs

This report provides a framework to support agencies in managing the associated risks and creating readiness for current and future technological innovations. Transformations in society, economy, and other underlying systems are also changing rapidly. They will need to become adept in operating under future circumstances to be successful.

The standard form of the risk matrix will need to be transformed into a tool that can respond to changes in information and be adapted to the needs of agencies addressing objectives in their regions, including disruptive technology and the transformation of modal forms and shares. Agencies must become both foresightful and resilient.

The methods are intended to support agency risk management. In developing this framework, the report drew novel analytical decision-support methods being applied in transportation but also on the application of leading-edge tools for decision-making under uncertainty that are being applied in nontransportation agencies involved in other aspects of public policy, such as water or energy planning.

The components are intended to provide value to state DOTs and MPOs through a new framework to strengthen agency resilience to emerging technologies. The combination of the components in this study offers a holistic approach for agencies to proactively and resiliently manage existing and new emerging technologies.

CHAPTER 1

Innovative Transportation Technologies and Risk Management

On April 3, 1860, the inaugural journey of the Pony Express left St. Joseph, Missouri, and delivered its first pouch of letters to Sacramento in 10 days. Hundreds of thousands of dollars were invested in the project, which took 186 stations and over 400 horses to connect California to the rest of the nation. However, this method of communication collapsed in just 18 months; it was made obsolete by the transcontinental telegraph.

The challenge of anticipating and managing the risks that emerging and disruptive technologies pose to transportation is not new. However, too often, technology catches practitioners by surprise, upending plans, hollowing out investments, and obstructing the achievement of critical transportation goals.

Those most affected by the variable fortunes and uncertainties surrounding new transportation technologies are likely to be the investors in, operators of, and customers using these innovative modes. These groups will also be the principal drivers of change. Public transportation agencies have been charged with ensuring success in carrying out the mission of achieving good outcomes for the societal goals assigned to them: safety, mobility, sustainability, planning, and equity, among others.

This compounds the problem of risk management for transportation agencies. Although regulatory and other connections intertwine agencies and agency planning and policies with decisions made by the private sector and the public, the trajectory of how various transportation modes evolve and how they will affect the mission goals of agencies is far from being under the control of those agencies. The risk management challenge for a transportation agency might therefore be somewhat less straightforward than for the owner and operator of a chemical plant or oil-refining facility.

The inability to fully anticipate technological futures—to say nothing of the impact of those technologies on the societies that employ them is not a failure of due diligence. Rather, it is inherent in the enterprise of innovation. Decades of research and practice have produced a knowledge base that may be used to manage the risks posed by running an industrial plant and even, to some extent, those surrounding familiar transportation technologies. The goal of this report is to assist transportation agencies, both state DOTs and regional MPOs, in achieving a more resilient posture in managing risks that may arise from introduction and adoption of emerging and disruptive transportation technologies.

Overview of Research Parameters

This section describes the main parameters that govern the treatment of agency risk management.

A Guide for Readers of This Report

For readers interested in risk associated with specific technologies, Chapter 1 provides useful background, but the reader might begin with Chapter 2, which describes the risk register format and then select among Chapters 3 through 6 for the specific technology of interest.

For those interested in risk to specific agency goals, Chapter 1 provides useful background, but the reader might begin with Chapter 2, which describes the risk register format. Appendix A consists of a statistical breakdown of risk priority among agency goals. Turn to Appendix B for the full risk register arranged by agency goal and risk priority. Further information on specific sources of risk may then be obtained by using the unique identifier associated with any row in the Appendix B risk register to identify additional information found in Chapters 3 through 6 in Tables 3.1b through 6.1b as well as the literature review provided in each chapter.

For those interested in agency risk management, Chapter 1 provides the background of this report. Chapter 2 describes the risk register format. Appendix C describes the method used to develop the risk register as well as guidelines for how agencies may both modify its entries and tailor the tools used to develop it to local circumstances and priorities. Chapter 7 provides primers on high-level policy and strategy to enhance the resilience of transportation agencies while Appendix D provides fuller versions of these briefs. Appendix A contains a statistical breakdown of risk priority among agency goals and technology groups.

For those interested in methodological innovation, Chapter 1 provides useful background, and Chapter 2 describes the risk register format and approach. Appendix C describes the method used to develop the risk register as well as guidelines for how agencies may modify its entries and also tailor the tools used to develop it to local circumstances and priorities.

Two issues make use of standard risk management approaches difficult for transportation agencies facing emerging and disruptive technologies: (1) the difficulty of assessing the likelihood of risk in the presence of the uncertainty surrounding technological innovations and (2) the heterogeneity of potential consequences given the range of agency goals. The research approach taken for these two issues is detailed in Appendix C.

Key goals of this research are to

- Develop a register of risks to state and local transportation agencies and their constituents posed by emerging technologies.
- Recommend approaches agencies can use to prioritize those risks.
- Identify policies and actions to address the risks along with the potential impacts of those policies and actions.
- Focus on four examples of innovation in transportation: connected autonomous vehicles (CAVs), electric vehicles (EVs), mobility on demand/mobility as a service (MOD/MaaS), and advanced air mobility (AAM).

Research Method

The research team conducted a literature review of hazards associated with the four technology groups and the agency goals defined by the NCHRP Project 23-15 panel. Results were placed within a common framework. Gaps (in the form of unanswered questions) were identified. These gaps became the focus of questions and themes for the peer exchanges on mobility and safety, sustainability, and equity. Each session had 8 to 12 participants. The team selected participants from planning and policy staffs of state DOTs and MPOs and representatives of other government agencies, but also researchers, staff of nongovernmental organizations (NGOs), and representative stakeholders from both business and local communities. Appendix C describes the methodology of the peer exchanges. Using outputs from the peer exchanges and the results of the literature review, the research team identified the hazards to be included in the risk register. These were potential deleterious outcomes from the application of the new technologies as well as missed opportunities for failing to advance agency goals through technology use. The methodological approach for assessing risk priority was developed as described in Chapter 2. This was refined over several iterations to test the capacity to accommodate the range of cases being examined. Care was taken to adapt the risk register to an environment where little data on probability and scale of hazard occurrence were available.

The methodology used to generate the risk register was reviewed. All participants in the peer exchanges were invited to an online presentation and discussion of the methodology for their review and input. A workshop attended by staff from the Southern California Association of Governments (SCAG) and the California Department of Transportation was held at SCAG headquarters. Teams of attendees worked on actual assessments of risk and risk priority by employing this report's methods.

The second part of the review was the development of high-level policy and strategy primers aimed at presenting broader, high-level risk mitigation strategies and policies sufficient for implementation in a technology-agnostic manner across agency goals. These were constructed by analyzing the columns in the risk register that listed actions that could be taken to mitigate the consequences of the risks implicit in each of its rows and noting commonalities.

The products from this report seek to provide state DOTs and MPOs with a new framework to strengthen agency resilience to risk from emerging technologies. The report offers a holistic approach for agencies to proactively manage risks latent in existing and newly emerging technologies. Furthermore, the methodology outlined in Chapter 2 can be used to compare different approaches based on geographies and has the potential to foster information sharing among state DOTs or MPOs. Appendix C contains a detailed description of the methodology.

Four Technology Groups

Detailed literature reviews on sources of risk for the four technology groups appear in Chapters 3 through 6. This section provides brief overviews of those four groups.

EVs. The distinguishing feature of modern EVs is their power source; instead of relying on internal combustion engines (ICE), they use battery packs that store electrochemical energy that can deliver current to an electric motor on demand. There is also ongoing work on a class of EVs that generate electricity using hydrogen fuel cells. There are several subcategories of EVs. Hybrid electric vehicles (HEVs) are vehicles that have both an engine with a fuel source and a battery-powered electric motor. However, not every HEV can be charged externally; those that can are referred to as plug-in hybrid electric vehicles (PHEVs). A vehicle without any ICE and powered solely by an electric motor is termed a battery electric vehicle (BEV) and can be charged externally. An umbrella term used to capture all vehicles that can be plugged into charging infrastructure like PHEVs and BEVs is plug-in electric vehicles (PEVs). This report will refer to both BEVs and PHEVs as EVs. When referring to the size and ownership of vehicles, the following terms are used: passenger light-duty vehicle (PLDV), medium-duty (MD) vehicle, heavy-duty (HD) vehicle, and light commercial vehicle (LCV).

Transportation electrification is increasingly seen as critical for reducing greenhouse gas (GHG) emissions. Many government entities and corporate policies have come to support transportation electrification (Kapustin and Grushevenko 2020). Technical improvement and rising commitments to EVs from automakers present promising growth in EVs (McKerracher et al. 2022).

The time and resources available for this report did not permit delving into the distinctions between alternative energy fuel paths for EVs. While the focus is on battery storage, much of the information may apply to hydrogen fuel cell alternatives.

CAVs. Autonomous vehicles (AVs), also referred to as “driverless,” “autonomous,” or “self-driving” cars, are “vehicles that perform all driving functions with or without the human driver” (Pieroni et al. 2018), including “steering, throttle, braking, and motive power selection (forward, reverse, and other), with various levels of occupant involvement or monitoring” (Maddox et al. 2015). Such vehicles might be owned by private parties or may be shared among multiple users, referred to as shared autonomous vehicles (SAVs) or shared autonomous electric vehicles (SAEVs).

Connected vehicles (CVs) have “applications, services, and technologies that connect a vehicle to its surroundings” (Uhlemann 2015). They enable direct or indirect communication to and between vehicles by using technologies that include but are not limited to direct short-range communications (DSRC), cellular telephony, Wi-Fi, or satellite (Maddox et al. 2015). Surroundings in the CV context refers to vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I).

CAVs have connected and autonomous driving capabilities. Wadud et al. (2016) estimated, based on a survey of self-identified experts, that vehicles would be capable of driving themselves on urban and rural surface roads and highways by 2025, and doing so in a failsafe manner (without a human driver backup) by 2030. More recent projections are less optimistic [e.g., Metz (2021)]. Adoption of CAV technology by consumers is wrought with uncertainty, with most estimates derived from volunteer, self-reported survey data. For example, a survey of about 600 respondents from Austin, Texas, revealed about half of the respondents were likely to use CAVs and half were unlikely to use them. Boston Consulting Group anticipates that it will take 15 to 20 years for AVs “to reach a global market-penetration rate of 25%” (West 2016).

As with the other technologies, it remains to be seen how CAV technology and systems will be embodied in new transportation products. This report emphasizes shared-use CAVs (currently in testing phases) because it appears that this form and usage (i.e., robotaxis) are likely to emerge first on U.S. roadways. However, much that is discussed in this report could apply to private-use CAVs as well as freight. The method used to construct the risk register may be used to create additional rows for sources of risk to agency goals arising from these applications.

MOD/MaaS. MOD is the “concept envisioning an interconnected and coordinated mobility ecosystem to meet the needs of all users by providing the safe, reliable, and efficient movement of travelers and goods. MOD offers users personalized mobility and goods delivery options on request, matched with coordinated network strategies of services providers and operations managers” (SAE 2021). MOD takes a user-focused approach to ensure that new emerging modes are “developed alongside existing services in an integrated fashion to foster a fluid and connected transport system incorporating all modes and people in a seamless fashion” (U.S. DOT 2023).

MaaS is a "concept envisioning integrated mobility where travelers can access multiple transportation modes over a single digital interface. MaaS primarily focuses on passenger mobility allowing travelers to seamlessly plan, book, and/or pay for travel on a pay-as-you-go or subscription basis" (SAE 2021). While MOD focuses on the user, MaaS focuses on the technological aspects, enabling users to plan, book, and pay for multiple transportation modes using a single interface (AASHTO 2023). The MaaS customer uses a single application and payment channel to access mobility, regardless of the travel mode or the length or type of trip.

While MaaS is defined by the aggregation of interfaces and payment methods, MOD is the concept of consumers accessing mobility and goods delivery through multiple means, when and where they want it.

AAM. AAM is a broad concept focusing on emerging aviation markets and use cases for on-demand aviation in urban, suburban, and rural communities. AAM includes local use cases of about a 50-mile radius in rural or urban areas and intraregional use cases of up to a few hundred miles that occur within or between urban and rural areas. AAM includes passenger mobility, goods delivery, and emergency services in urban and rural areas [commonly referred to as urban air mobility (UAM) and rural air mobility, respectively] (Cohen et al. 2021; Reiche et al. 2018).

A variety of technological advancements and industry investments in electrification, automation, vertical takeoff and landing (VTOL) aircraft, uncrewed aerial systems (UAS), and air traffic management are enabling innovations in aviation such as new aircraft designs, services, and business models. Several companies have announced plans to launch passenger AAM services using VTOL and other novel aircraft designs beginning in the mid-2020s. A few prepandemic market studies estimate the potential for scaled operations and profitable services in the late-2020s and early 2030 (Cohen et al. 2021; Goyal et al. 2021; Hasan 2019; Morgan Stanley Research 2019; Porsche Consulting 2018; Reiche et al. 2018).

Of the four technology groups, AAM is in several ways the most difficult to treat in a risk register format. EVs are on the road, people are using the first MOD/MaaS services, and CAVs in the form of "robotaxis" are being tested. Yet, AAM represents a diverse group of technologies, use cases, aircraft, and operations. Additionally, AAM may be piloted, remotely piloted, or fully automated, with unique types of risks associated with varying types of automation.

AAM should be viewed as representative rather than comprehensive. As AAM technologies emerge, agencies may add additional rows to the risk register for sources of risk for these farther off applications.

Agency Goals: What Is at Risk?

The concept of risk contains within it the concept of threat. What may be at risk if exposure to a hazard occurs and vulnerability to that hazard is present? What are the potential losses or gains for transportation agencies?

This report focuses on a selection of agency goals derived from U.S. DOT reports, noteworthy emerging mobility plans, and participants in peer exchanges. These outward-facing goals, along with several agency goals categorized as inward-facing, were used as search terms in tabulating risks to agencies:

- **Equity.** The equity goal seeks to "reduce inequities across our transportation systems and communities they affect. [It also seeks to] support and engage people and communities to promote safe, affordable, accessible, and multimodal access to opportunities and services while reducing transportation-related disparities, adverse community impacts, and health effects" (U.S. DOT 2022d).

- **Environment and Sustainability.** To increase the sustainability of the transportation system, agencies need to "substantially reduce GHG emissions and transportation-related pollution and build more resilient and sustainable transportation systems to benefit and protect communities" (U.S. DOT 2022d).
- **Mobility.** Mobility is the ability to move quickly within and throughout a transportation environment to different activity sites. One means for enhancing mobility is accessibility, the number of activity sites available within a given distance or travel time (Giuliano and Hanson 2017, Ch. 1). Emerging mobility technologies have the potential to increase congestion—and therefore reduce mobility—due to induced demand brought by lower operational costs.
- **Safety.** The reduction and elimination of fatality and injury from the nation's roads are stated as the number one priority of the U.S. DOT. Each operating administration under U.S. DOT's jurisdiction takes a safety-first approach to providing transportation services.
- **Security and Privacy.** One major objective of the U.S. DOT's Strategic Plan is to "strengthen transportation system resiliency to protect it from disruption from cyber and other attacks" (U.S. DOT 2022d). Failure to maintain a secure transportation system could lead to connectivity challenges and individuals' compromised safety and privacy.
- **Public Acceptance of New Technologies.** How well and how readily the public accepts new technologies may be a factor in achieving other agency goals.
- **Public Health.** This category was used to include factors that would support or detract from public health other than those included in the category of safety.
- **Inward-Facing Agency Goals.** Agencies should individually or collaboratively define inward-facing goals so that they can then identify consequences that may result if the goals are

Basic Definitions of Risk

While this report is not intended to substitute as a manual on agency risk management, it is important to define risk and the concepts that underly it. These definitions are used within this report.

Risk arises from a combination of hazard, likelihood, and consequence.

Source of Risk ("Hazard") is an event or condition that might lead to risk for an agency goal or objective. The technical literature speaks of "hazard," but that term does not fully convey the sense in which risk is seen to arise in the specialized setting of transportation, where a beneficial outcome in some respects might be a source of risk in another. In this report, the terms "hazard" and "source of risk" will be used interchangeably.

Likelihood is most often expressed as a probability of occurrence. Such a probability is often difficult to gauge accurately for emerging technologies in their early stages.

Consequence is usually calculated as the loss (or gain) that occurs when a hazard materializes and changes the outcome from what had been expected. Consequence may be affected by degree of exposure to a hazard as well as factors that would raise or lower individual agency vulnerability to it. This report includes exposure and vulnerability within the concept of consequence and does not treat them separately.

compromised. Examples in this category include the goals of budgetary solvency, limitation of tort liability, workforce adequacy (both within the agency in terms of access to necessary skills for understanding changed requirements associated with emerging technologies and within the wider economy for those technologies' safe and effective operation), data governance, and changes in agency goals as a result of societal change from technology adoption.

In the risk register framework, the outward-facing goals appear first, public acceptance of new technologies and public health are placed together in the category of Other, and internal agency goals are treated as one large set.

Risk versus Hazard

Because of the need to speak with precision about potential actions that transportation agencies may take or postures in which to place themselves to better mitigate risk, it is useful to speak with precision about the concept of risk.

Risk arises from some underlying cause or event, a "hazard." A hazard, however, may not lead to consequences for one or more agency goals. Risk arises from a hazard depending on the *likelihood* of an event occurring (e.g., the deployment of EVs as luxury vehicles) and some measurable *consequence* for some specific agency goals (e.g., transportation equity). For this project, emerging and disruptive transportation technologies can also present an *opportunity* if they enable an agency to meet its goals better than it currently can. Thus, there is a risk of a missed opportunity. For instance, widespread use of EVs presents an opportunity to meet transportation sustainability goals (e.g., reducing GHG emissions), but public investment in charging infrastructure is necessary to realize that opportunity. Failing to invest in charging infrastructure risks missing the opportunity that EVs offer.

Risk management requires understanding threats and opportunities and planning to avoid or manage them. The challenge in the management of risk associated with emerging and disruptive technologies is that there is considerable uncertainty. Such uncertainty is inherent in the enterprise of technology innovation and adoption. Formal tools of risk management can be applied when likelihoods are well understood and the hazards that may occasion risk to agency goals or operations have been cataloged. There is little consensus on hazards, likelihoods, or consequences. On the other hand, consensus formed too early could prove in the long run to increase risks. The opportunities for surprise would multiply. Therefore, risk management also includes identifying and prioritizing *actions* to manage these uncertain risks. The first step is to form a base of knowledge.

Risk Management in an Era of Change

Agency risk managers realize that it is not possible to achieve and sustain a static posture for risk management because of the velocity of technological change; the interconnections between different technologies, existing systems, and economic and social processes; the complexity and far from well-understood character of those relationships; and changing roles for transportation agencies. Rather, the best stance that managers can take is to determine how they can enhance resilience as a property of their organizations and processes. This report is intended to assist them in moving toward such a posture.

> "New fast-moving technology-based trends are characterized by uncertainties, and the main criteria that . . . officials use in deciding how to respond . . . do not address uncertainty" (Government Accounting Office 2008).

Risk registers work well for processes for which there are historical practices and databases of experience to draw from. Constructing a risk register that will stand the test of time may not only be impossible but may be a disservice to agencies. Overconfidence stemming from misplaced concreteness is one of the leading causes of both surprise and underestimation of the level of risk an agency might be exposed to.

The risk register is illustrative rather than comprehensive: A snapshot based on what agencies know and are experiencing with these emerging technologies at the time the report's research was carried out. It has been constructed from the perspective that agencies will need to update it at regular intervals—similar to the agency practice of performance management. This report anticipates and provides guidelines for how revising the risk register to address local conditions and concerns.

During the study, it was determined that a traditional risk register alone would be insufficient to support agencies appropriately. The report therefore includes materials in addition to the risk register. The report derives from the risk register an overview of the mitigating actions that agencies might employ to address the risk presented in its rows. A small number of high-level policies or strategies would enhance the ability of agencies to maintain resilience in the face of shifting risks as well as develop and implement actions that would be robust to the plausible future implicit in the different trajectories new technologies might follow. Short versions of these primers are found in Chapter 7 while more detailed versions are presented in Appendix D.

Outline of This Report

Chapter 2 lays out how agency staff may use the risk registers presented in the subsequent chapters. (Appendix C contains a more detailed discussion of the issues involved with risk management in the face of emerging and disruptive technologies being adopted into the systems involved in transportation. It outlines the steps and explains the tools developed to construct a risk register for the risks raised by the four technology groups. This appendix also explains how agencies may then use this framework to both adapt it to the circumstances of their locale of jurisdiction as well as update the risk register as conditions in their regions or those surrounding the technologies may shift).

Chapters 3 through 6 present the risk register by technology group. The risk register and its accompanying risk matrix for calculating relative priorities among sources of risk across the four technologies and a range of agency goals constitute the principal focus of this study. Each chapter includes literature reviews of sources of risk for that chapter's technology group. (Appendix A provides a statistical overview of risk priority across all rows of the full risk matrix while Appendix B presents the full set, this time grouped by agency goals).

Chapter 7 looks across the mitigating actions present in the risk register and derives from them a small set of higher-level policies or strategies for agencies to use. The guidelines included in the chapter are intended to place agencies into a more resilient posture for handing technological risk. These guidelines are reflective of the current mitigating actions at the time of this publication and serve as a useful template to be updated by agencies when going through this process. Short overviews of these topics are provided in this chapter while Appendix D provides more detailed expositions.

Chapter 8 concludes with how agencies can operate with greater confidence as they enter an era with uncertain risks.

CHAPTER 2

How to Read the Risk Registers and Risk Priority Rankings

The risk register serves as a starting point to identify potential threats or opportunities, not as the final word for all transportation agencies and all potential emerging and disruptive technologies. Transportation agencies can use this baseline, the methodologies that have been outlined, assessments of local conditions, and their own priorities to modify as well as update the risk register to build a resilient posture toward the management of risks from transportation technology innovations and their adoption.

This chapter presents key points for understanding how the risk register in Chapters 3 through 6 should be interpreted and used.

Risk Register Format

The risk register is intended to contain consistent information on risks from emerging and disruptive technologies in a single framework. It is the synthesis of research on hazards associated with the four technology groups. Each row of the risk register enables users to gain specificity on one pairing of technology with one of the potential hazards to agency goals. The framework is divided into four sections as shown in Table 2.1. The format is a modification of the standard approach to risk register design. It contains several novel features as described.

Potential Sources of Risk

This section of the framework keys each row to one particular risk source (or hazard) emanating from one of the four technology groups. Note that a hazard might appear more than once in the risk register if it could evolve from several of the technologies. Each hazard/technology pair would appear as its own row.

The **Risk Source [Hazard]** column contains a description of the hazard/technology pair.

The **Signpost Indicators to Watch** column contains one or more indicators that would aid agencies in monitoring the progress of the risk source over time. Such a signpost indicator may be keyed directly to performance with respect to the agency goal under threat or might be a proxy that is thought to be directly (or inversely) connected with the value being tracked.

The signpost is intended to suggest an early warning of how the future and any related risk are unfolding. If data are not readily available, this column serves as a gap analysis of what information could usefully be actively monitored going forward. The concept is to point toward what might be a useful metric rather than selecting among only those time series that might currently be available. By taking a data-centric approach to risk monitoring, tolerance levels can be assigned to time series data to alert users when signposts are trending unfavorably.

Table 2.1. Risk register format.

Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Risk Priority
Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	Priority Score

The **Likelihood Proxy** column presents the output of either the SI-LOC or CB-LOC measure as a proxy for otherwise unknown likelihood. In the absence of other information, the **CB-LOC** measure is an assessment based on a decomposition of the nature of the hazard/technology combination. The **SI-LOC** measure is based on observation of data obtained on one or more measures chosen to provide early warning guidance associated with the hazard/technology combination. This is one aspect of the intended flexibility in the framework. For emerging transportation technologies with few identified data sources pertaining to the specific risk source, the use of the CB-LOC measure provides an approach to discerning how a risk source should be assessed with respect to prioritization based on assigning ratings to key features. More established transportation technologies, like BEVs, are likely to have more data available for constructing the SI-LOC measure.

For an identified signpost with such data, the SI-LOC measure allows for hazard prioritization based on time series data trends. This column of the risk register displays one of the two LOC measures as the likelihood proxy score with a color coding. A standing heuristic is that if the SI-LOC measure can be calculated from available data, that score is reported in the risk register. Otherwise, the CB-LOC measure is used.

Potential Consequences for Transportation Agency Goals

This section of the framework describes the potential effects on agency outward- and inward-facing goals of the hazard/technology pair and a judgment of the magnitude of that impact.

The **Goal Affected** column identifies which specific agency goal the risk source may influence. One risk source can affect several agency goals. Appendix C contains a discussion of how to use the framework for a risk source affecting more than one agency goal.

The **Potential Consequences** column provides a description of what might ensue from the risk source for the previously described agency goal.

The **Severity Score** column provides the output of the user's selection from the severity of consequence scores (see Table C.4) used to determine the relative level of consequence a risk source might have on one of the main outward-facing agency goal categories or on an issue that constitutes one of the inward-facing goals (represented by a single column in Table C.4). As with all aspects of the framework, the expectation is that as embodiments of the four technologies become clearer, knowledge and experience are gained, and local needs, circumstances, and interests are defined, local agencies will modify the criteria for ascribing relative consequence severity to suit their regional profile and purposes.

Transportation Agency Policies and Actions

This section of the framework lists a representative selection of mitigating actions available to transportation agencies that arose from the literature review and the peer exchanges.

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The **Potential Mitigating Actions** column lists the policies and best practices suggested or being used.

The likely or possible **Action Owners** are listed in the next column. This feature is present in some but not necessarily most traditional risk registers. In most engineering or industrial applications where risk is being managed by staff who reside in the same umbrella organization as those charged with operations and process issues, a risk register will not need to call out envisioned actors. Transportation agencies, however, are not often in a position to exercise direct control over technologies, their development and adoption, or their use. Further, in many cases, other agencies and different levels of government may be involved in mitigating hazards that raise risks. Therefore, making this context explicit is an important element for a risk register of risk stemming from emerging and disruptive technologies.

Risk Priority

The **Risk Priority** column contains the priority score, which is the ranking of the risk for a particular technology. The score is the output of the risk matrix (sometimes referred to as a risk priority "heat map") and is used to assess the overall risk for the specified agency goal. The risk matrix receives the consequence severity score (as determined by Table C.4 or a similar ranking of severity) and the LOC score as a likelihood proxy and then assigns a risk priority score in a manner described in the next section.

It is important to note that this priority score is the risk before any risk mitigation strategies are implemented. Once a strategy has been decided and its implementation commences, reevaluating the total risk after mitigation is likely to reduce the risk priority score.

Practical Issues with a Risk Register of Emerging and Disruptive Sources of Risk

Risk Management

Risk management is an important function of organizational planning and leadership. Risk management addresses the potential consequences of uncertainty on an organization's strategies and operations for achieving its objectives. Transportation agencies face uncertainty due to a pervasive dynamic of change in many systems, and they may face even more when encountering emerging and disruptive technologies.

This report is not intended to substitute as a manual on agency risk management. Rather, it seeks to enhance the implementation and performance of risk management procedures. [External sources for reviewing current methods for risk management include publications available from the ISO, IEC 31010 (International Organization for Standardization 2019) and the AASHTO Guide for Enterprise Risk Management (2016). See also Curtis et al. (2012).

Risk Registers and Risk Matrices

Risk registers are used by engineers to catalog and share knowledge about hazards that might arise, how likely such hazards are, what the consequences might be from a hazard event, and what mitigating steps may be taken through active risk management. Risk registers are usually accompanied by a risk matrix (heat map), which aligns likelihood of hazard with severity of consequences to develop a priority ranking of hazards that should receive the most organizational attention. The greater the likelihood of a hazard or the greater the severity of potential consequences, the greater the assigned priority.

The literature on risk registers also describes some of their shortcomings. Risk registers run the risk of separating risk management from other core management activities by focusing solely on hazards, usually of either natural or human-made origins, but almost exclusively on the types of events that have deleterious consequences and that may be insured against. In engineering or industrial plant applications, risk registers rarely if ever account for the risk inherent in failing to take advantage of opportunities.

There are practical problems with risk registers as well. Their line-by-line layout does not represent mitigating actions that may affect more than one hazard and goal combination, or in the context of this report, the combination of hazard and transportation agency goal with specific novel transportation technologies. Though convenient as a bookkeeping protocol or representational format, hazards and likelihoods may not truly be as conveniently separable line-by-line as the rows in a risk register might suggest. They may instead be compound, causally related, or correlated.

While one should be aware of the limitations of the risk register format, framing and populating risk registers for the emerging technologies of AAM, CAVs, EVs, and MOD/MaaS still provide practical value. It is a format that many transportation agency staff will be familiar with, which might ease its use and public acceptance.

To avoid potential pitfalls, agencies should be aware of two principal issues. For early-stage technologies, risk registers run the risk of conveying a distorted view of the uncertainties involved, particularly regarding likelihood. They can give a sense of greater accuracy than they do or can possess.

The other issue stems from the nature of transportation agencies. Agencies are not often the investors, owners, or operators of the technologies involved. Instead, they have a heterogeneous portfolio of societal goals of which they are either the principal or collaborative stewards. This makes applying a traditional risk register perspective insufficient unless explicit recognition is made of their responsibilities and the environment in which they operate.

The Problem of Likelihood

For emerging and disruptive technologies, likelihood represents a core uncertainty. This is true for the various sources of risk, including technologies such as EVs and MOD/MaaS. Measuring uncertainty associated with emerging technologies such as CAVs and AAM is more difficult. The literature review did not yield many likelihood estimates for specific hazards. Further, during the peer exchanges, though participants were encouraged to provide their estimate of hazard likelihoods (indicating "low," "middle," or "high"), almost none did so.

The report suggests proxies for likelihood to use in the risk registers rather than attempt to guess at the probability statistics. Attempting to provide probabilities would risk conveying a concreteness that is not available at this time. It would also run the risk of masking the variation in the quality and quantity of the present knowledge across all sources of risk associated with the four technology groups.

The proxies for likelihood were developed by first asking what role likelihood plays in a traditional risk register. For most users, they are taken as a measure of how concerned to be about a source of risk. A potential for risk, or a hazard, may have a high consequence if it becomes realized. But if the likelihood for the hazard transpiring is low, a risk register will usually key the hazard at a lower priority than one for which the likelihood/consequence combination is higher.

This line of reasoning led to the consideration of two approaches—not so much as replacements for likelihood but rather as acceptable measures of "degree of concern" that should be brought to the risk management process by agencies confronting emerging and disruptive technologies under uncertain and dynamically shifting conditions. Both should play a role going forward in finalizing the current version of the risk register. These will be described here.

The Problem of Heterogeneity

Another conceptual issue arises when comparing risk management in a transportation agency facing emerging technology to that in an actively producing industrial facility. In the latter case, there is a bottom line that provides a consistent basis for comparison. This is less true in activities that may result in externalities, such as emission of effluents, or in loss of life or injury to human beings. But even in those cases, legal frameworks and actuarial tables can provide some consistency. The many different goals that transportation agencies have as mission agencies make such comparisons more difficult. It is hard to describe a consistent bottom line among goals of mobility, safety, equity, sustainability, privacy, and so forth. Further, there may also be different answers to the question of who bears the costs and therefore the risk involved. These, in turn, may vary by locality.

The issues of proxying likelihood and the heterogeneity of transportation agency goals required developing a method to provide a consistent, integrated risk register of sources of risk emanating from the adoption of products and services from four emerging and disruptive transportation technologies. Appendix C provides more detail on this approach. The following sections present aspects of this method that will enable the reader to interpret the results found in Chapters 3 through 6.

How Likelihoods Are Represented in the Risk Register

One of the key components of risk analysis, likelihood of occurrence for a hazard, cannot be included in this risk register. The preliminary or even prospective nature of many potential hazards from technologies not yet in common use preclude forming reliable estimates. Therefore, as discussed in Appendix C, measures for inferring an LOC have been calculated in lieu of an estimate of likelihood.

Two LOC proxies, depending on the level of available information, stand in for the experience and well-understood best practice that is lacking for early-stage technologies. The CB-LOC measure is an assessment based on a decomposition of the nature of the hazard/technology combination. The SI-LOC is based on observation of data on one or more measures chosen to provide early-warning guidance associated with the hazard/technology combination. These both stand in as crude proxies for likelihood in the sense that a higher likelihood would, all things being equal, yield a higher LOC for a potential source of risk (hazard) associated with an emerging or disruptive technology.

In the early stages of technology rollout, there will not be sufficient data to construct a meaningful SI-LOC measure. Only an estimate based on observed or anticipated characteristics of the hazard/technology combination would be available. At a later stage, time series data will exist to make it possible to construct the data-based SI-LOC measure. This latter measure should be privileged over the CB-LOC measure. It will be based on actual data to construct an indicator that regional transportation agencies find reasonable and in line with local conditions.

For this reason, the likelihood proxy in each row of the risk register will report a representative signpost indicator measure if available. If not, that number will instead represent the characteristics-based measure. Below the risk register tables, the user will find a second table indicating how the SI-LOC and CB-LOC measures (likelihood proxies) were evaluated for each row in the risk register. For some, the SI-LOC can be used while for others only the CB-LOC. A hazard that has already begun to occur can be assigned a 3 while one yet to manifest itself can be assigned a 4.

Signpost indicators appear most in the register entries applying to EVs and MOD/MaaS. This is due to the availability of time series data. The actual entries should be considered as examples only—starting points for agencies to build on and to be either configured to regional circumstances or replaced entirely by other candidate signpost indicators. In the examples, some make use of national data while others draw on more regional sources. This, too, is a design choice for agencies. Depending on the type of early warning desired, both scales could be useful to monitor.

How Risk Priority Is Assessed in the Risk Register

Figure 2.1 illustrates the method for assigning consistent risk priorities across hazards associated with technology groups and across the full range of agency goals. Proceeding from the upper left and moving downward, once a hazard is identified it is mapped to an agency goal potentially at risk. Appendix C describes in detail a scale for severity of consequences by which each row of the risk register is assessed. Beginning once more with the identified source of risk, the assessment moves to the right. Depending on data availability, either the SI-LOC measure or the CB-LOC measure is determined and used as a likelihood proxy. This score, along with the previously determined consequence severity score, are the two principal inputs to the risk matrix appearing in the bottom right of Figure 2.1. Finding the corresponding rows and columns keys out the level of risk priority assigned to the hazard/technology combination appearing in the associated risk register row.

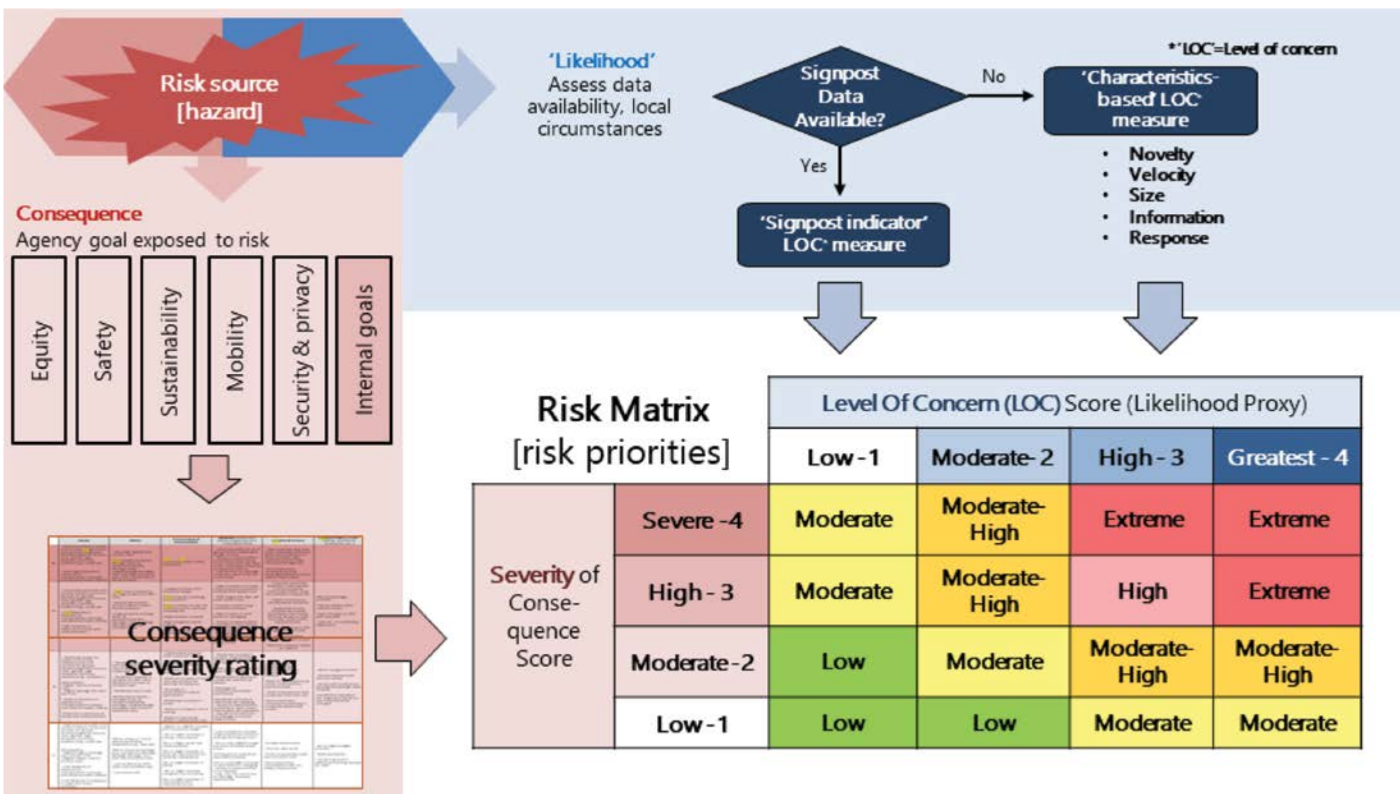

Figure 2.1. Diagram of risk priority assessment process.

It may well be that results from assigning risk priority will differ depending on whether the SI-LOC or CB-LOC measure is used as a proxy for likelihood in the risk matrix's columns. This discrepancy might be more apparent than real. The signpost indicator measure would not only be based on actual data but the indicator itself would have been selected because of a perceived relationship to the agency goal being considered. In the absence of further information, the risk priority score yielded by using this (SI-LOC) data-based measure should be privileged over the one that would be based on assessment of perceived characteristics of the hazard/technology combination (CB-LOC) in that row of the risk register.

Timing. As a general rule, the presumption is that assessments of the factors that feed into both alternative LOC measures (and therefore risk priority) are made from the perspective of the present looking forward. *Velocity*, for example, one factor entering into the CB-LOC measure, looks at both the speed of adoption and envisioned scale of potential adoptions. This assessment would be based on estimates and evaluations currently available. This is one of the reasons for regularly updating the risk register to account for changing information and assessments. All assessments given in this chapter's risk register are made before any mitigation actions are taken.

Scale. The number and size of groups affected, either in terms of the range of potential technology adoptions or the exposure to potential consequences, arise at several points in the risk register. Both measures of LOC as well as the severity score attached to specific consequences have elements of scale in their composition and calculation. However, the magnitudes of scale effects will be case-dependent. The correct basis for judgment will need to be tailored to the source of risk being described.

As an example, the highest-level score for severity of consequences is a 4, which is reserved for instances of risk of serious injury or loss of life, widespread economic loss, or the spread of grievous inequity. But how much loss of life, for example, will rate a 4? If the United States were to register 30,000 traffic fatalities a year instead of the current higher level, that would be counted as an improvement. On the other hand, fatalities or serious injuries from CAV operation might be viewed as more consequential at a far lower level. Some experts have noted that AAM's safety is existentially important because of planned operations at low altitudes and overpopulated areas (Cohen and Shaheen 2022). As such, AAM will need to be considerably safer than even that of commercial aviation (Christopher Hart, undated personal communication).

This factor reinforces the point that, as with all such rules governing the construction of risk registers in Chapters 3 through 6, individual agencies will need to modify them or establish guidelines suited to their own purpose and regional circumstances.

Differences from Conventional Risk Registers

Readers familiar with risk registers and risk matrices will find in the tables in Chapters 3 through 6 several features not routinely found in more traditional presentations. This is largely owing to the data in the tables not emerging from engineering, industrial, or operational experience; in most cases, such experience does not yet exist for these technology applications. In addition to those noted previously and in Appendix C, there are several principal differences from usual practice.

- Because of both the lack of available experience and the prospective nature of much that is covered in this review, the risk registers are not intended as static compilations of statistical data. They are intended to serve as a foundation and a framework for adaptation and review by individual transportation agencies. These risk registers are intended to be dynamic, changeable, and tailored to local circumstances, priorities, and updates of information.

- The concept of signposts is not found in most traditional risk registers. As discussed in Appendix C, these are intended to be tailored early warning indicators of the direction, rapidity, and form of change. Examples of possible signposts are offered in the risk register rows. In several cases, the team has been able to offer sample indicators based on these signposts for which data are available. These are mostly found in the EV risk register (Chapter 3), which is the technology farthest along in deployment. Agencies will need to construct the appropriate signpost and resulting indicators for themselves. As the examples in the EV risk register show, for some purposes, these might be based on national data or even international experience, depending on their intended use. In other cases, they may be constructed to reflect local experience and consequences.
- The risk register includes supplementary material describing the assessments that resulted in the SI-LOC and CB-LOC measures used as likelihood proxies in the rows of the main register. In keeping with the heuristic purpose intended by the research team, these assessments should be regarded as examples that agencies may follow to tailor their calculations to fit local conditions, priorities, and data availability.
- Some risk registers will assess risk priority before mitigating actions and after mitigation to express the residual exposure to risk. In this register, all entries are intended to reflect circumstances and risk priority before mitigation.

The risk register presented in Chapters 3 through 6 groups sources of risk (the rows) by technology. Each risk register is presented as a pair. The first table in each pair ("a") provides information typically found in a standard risk register (applying the exceptions noted previously). The second table in each pair ("b") provides data that underlie the calculation of both forms of the LOC measure. These data are useful for raising awareness of the relevant aspects of a source of risk from emerging and disruptive technologies to agency goals. Therefore, each pair of tables provides more detail than is typical of standard risk registers.

The tables are followed by a detailed review of the literature on risks associated with that chapter's technology group. These reviews were performed in spring 2022 and reflect the knowledge available at the time.

Finally, the same data found in the tables in Chapters 3 through 6 are presented in Appendix B arranged by agency goal.

How Sources of Risk Are Ordered in the Risk Register

Due to the intersectional nature of many of the hazard/technology combinations, a single pairing will likely affect more than one goal at a time. The risk register is framed to provide specificity of an individual hazard/technology pair's risk to a single agency goal. The convention adopted in this register is that if there are no changes to risk assessment or agency mitigation, both goals will be listed in the appropriate column of the hazard/technology row. If, however, there is a practical difference or the assessment of risk priority would change, it is best to add new rows for the same hazard but with a focus on the consequences and mitigations of separate goals. In this way, risk from intersectional hazard/technology pairs can be properly assessed without oversimplification or understatement of the risks involved.

The same may be true within a specific technological realm if that technology takes different forms. As discussed in Chapter 1, AAM may be embodied in products and services specialized for passengers, goods delivery/logistics, or emergency use cases. Each of these might exist in piloted, remotely piloted, or automated embodiments. The risk registers in Chapters 3 through 6 apply the perspectives outlined in Chapter 1 for each technology area. Over time, as the register is modified or made more comprehensive, the key concept for determining when more than one risk register row is required will be to ask what difference doing so would make to calculations of risk priority or recommendations for mitigation.

CHAPTER 3

Risk Register and Risk Priorities for Electric Vehicles (EVs)

EV Risk Register by Risk Priority

This chapter presents the risk register that resulted from applying the method outlined in Appendix C to the input received from a literature review and the results from peer exchanges. The team presents a synopsis of a literature review on agency risks associated with deployment of EVs, which will help agencies derive the full benefit of the risk register presented.

Literature Review on EV Sources of Risk

A literature review on the effects of EVs effects on agency goals was conducted. The following section provides a version of this review organized by agency goal. The material covered in each subsection is organized by the principal hazards listed in the risk register that follows.

Several agency goals mentioned elsewhere are not included in this literature review due to a lack of presence in the literature. These include public health, internal—workforce, internal—tort liability, and internal changes in role or mission.

Agency Goal: Equity

Traditionally, communities made disadvantaged have had unequal access to benefits from the transportation and energy system while being disproportionately exposed to high burdens from those systems (FHWA 2022a).

U.S. DOT's FY 2022–2026 Strategic Plan (2022d) defines the equity goal as "reduce inequities across our transportation systems and the communities they affect. Support and engage people and communities to promote safe, affordable, accessible, and multimodal access to opportunities and services while reducing transportation-related disparities, adverse community impacts, and health effects." This goal includes several strategic objectives: (1) expanding access, (2) wealth creation, (3) power of community, and (4) proactive intervention, planning, and capacity building.

EVs offer benefits to individual vehicle owners, communities, and businesses, including lower vehicle fuel and maintenance costs, improved local air quality, and economic development. Previous studies have focused on inequitable access to adoption of light-duty passenger EVs. Numerous sources discuss inequitable access to EVs. Pricing of EVs, incentive structures, and limited charging access have resulted in disproportionate ownership by privileged communities. Policies like the Bipartisan Infrastructure Law (BIL) aim to build a national network of EV charging stations and to address the equitable access to EV benefits like jobs and business opportunities created by the law. The National Electric Vehicle Infrastructure (NEVI) Formula Program guidance describes equity considerations related to EV charging stations (FHWA 2022b) as

- Improve clean transportation access through the location of chargers.
- Decrease the transportation energy cost burden by enabling reliable access to affordable charging.
- Reduce environmental exposure to transportation emissions.
- Increase parity in clean energy technology access and adoption.
- Increase access to low-cost capital to increase equitable adoption of more costly, clean energy technologies like EVs and electric vehicle supply equipment (EVSE).
- Increase the clean energy job pipeline, job training, and enterprise creation in communities made disadvantaged.
- Increase energy resilience.
- Provide charging infrastructure for transit and shared-ride vehicles.
- Increase equitable access to the electric grid.
- Minimize gentrification-induced displacement resulting from new EV charging infrastructure.

Three major hazards are identified from the literature that can potentially result in adverse consequences to transportation agencies' equity goal: (1) inequitable EV adoption, (2) disproportionate exposure to transportation emissions, and (3) electricity rate and affordability of charging.

Inequitable EV Adoption

Low-income communities and those made disadvantaged are likely to benefit the most from adopting EVs by reducing fuel and maintenance costs and community benefits such as improved air quality, health benefits, and widened economic development opportunities. Literature has identified two major contributing factors to inequitable adoption of EVs: (1) high up-front cost and (2) limited access to reliable and affordable EVSE. These barriers to acquisition have resulted in the majority of EV owners being male, high-income, highly educated homeowners, who have several vehicles in their household and have access to charging at home (Hardman et al. 2021). The literature also finds EV adoption in rural areas is about 40% lower than it is in urban areas (U.S. DOT 2022b).

The high up-front cost of purchasing EVs, lack of affordable vehicle options, and inequitable incentives limit lower-income earners from acquiring these vehicles. Luxury EV models are being introduced into the market and, even with decreases in battery costs, the average starting price of a BEV model has risen. In addition, inequitable structures of government incentives further hinder EV adoption beyond the privileged groups (Hardman et al. 2021). When equity is not incorporated in their design, funds are not distributed equitably. To take full advantage of income tax credits (ITCs) like those found in the Inflation Reduction Act, taxpayers need to have an adequate income, and members of the household must owe more in taxes than the amount of the credit. As a result, households with higher incomes and fewer children tend to receive higher tax credits than lower-income households with more children (Liu et al. 2022).

The second barrier is access to reliable and affordable charging. Unlike cost, which is similar across markets, charging infrastructure can present a localized barrier. Limited access to charging networks for rural and underserved communities and those made disadvantaged can exacerbate disparities in EV adoption (FHWA 2022b). As increased sales and economies of scale reduce production costs of EVs, the development of public charging stations is critical for EV owners who lack access to chargers at home or the workplace. Currently, in California, public EV charger access shows disparities based on race, ethnicity, and income, especially for areas with a higher proportion of multiunit housing. Communities with Black and Hispanic populations are significantly less likely to have access to public charging (Hsu and Fingerman 2021).

Signposts. Currently, it is difficult to evaluate a community's future exposure to inequitable access to EVs because no metric exists. However, agencies can monitor guidelines and resources that will be developed via the Justice40 Initiative (U.S. DOT n.d.a.). In July 2021, the White House released the Interim Implementation Guidance (referred to here as interim guidance) (2021b) for the Justice40 Initiative to provide the initial recommendations to advance equity in the nation. As part of the Justice40 Initiative and consistent with the interim guidance, the U.S. DOT and U.S. DOE have developed a joint interim definition of disadvantaged communities (DACs) for the NEVI Formula Program. There are tools and resources available to track the available charging stations and public investment in DACs, for example

- EV Charging Justice40 Map: A tool from Argonne National Laboratory providing interactive maps of communities made disadvantaged and public charging station locations (Argonne National Laboratory n.d.).
- Justice40-covered program benefits: As part of the interim guidance, agencies are required to develop methodology and metrics to measure program benefits that will be accrued to communities made disadvantaged.
- NREL EVI-Equity: The National Renewable Energy Laboratory is currently developing a model utilizing spatial analysis to evaluate equity aspects of existing vehicle electrification and charging station networks.

Likelihood. The research team found literature discussing inequitable access to EVs (Hardman et al. 2021; U.S. DOT 2022a; Liu et al. 2022) and disparities in access to reliable and affordable charging infrastructures (Hsu and Fingerman 2021; FHWA 2022b). Likelihood was not discussed because disparities and barriers have already been identified.

Consequences. Communities made disadvantaged have had disproportionate exposure to negative externalities from the transportation and energy system. Limited access to EVs and affordable charging networks can further exacerbate inequitable distribution of benefits from a cleaner transportation and energy system and limit the achievement of climate goals (Wissell et al. 2022). Clean energy jobs, economic development, and other positive externalities may also be at risk should EV adoption remain inequitably distributed.

Mitigating Actions. There is a cross-agency federal initiative to address the issue. The Justice40 Initiative aims to target at least 40% of the overall benefits of federal investments in climate and clean energy, including sustainable transportation, toward communities made disadvantaged. Access to affordable EVs, charging stations, and purchase programs are examples of the program's benefits.

Ensuring that equity is considered when designing policies to disperse EV incentives will aid DACs. State and federal DOTs, MPOs, and legislatures would be responsible for designing and implementing these policies. Several states are enhancing their policies to include equitable access to incentives by introducing eligibility qualifications for additional rebates based on income level and local air quality (Guo and Kontou 2021). In addition, incentives delivered at point of sale can make EVs more affordable than incentives received after purchase (Pierce et al. 2019).

Another way to prevent or mitigate this hazard is to provide reliable and affordable chargers in DACs. State transportation agencies would be responsible for the implementation of these policies by using tools like those referred to previously.

Gaps in Knowledge. The literature discusses disparities and barriers to EV access. However, there is little understanding of how to establish a target and evaluate progress (e.g., performance metric).

Disproportionate Exposure to Transportation Emissions

Certain communities suffer from disproportionate exposure to transportation emissions [e.g., diesel particulate matter (PM)], which raises environmental justice concerns. These areas are typically around distribution centers, mega warehouses, highways, and ports (Treebumrung and Lee 2021; Karner et al. 2009). Expansion of e-commerce has increased warehouse and logistics needs. Now, more warehouses and distribution centers are in low-income communities of color (Yuan 2021). The residences and schools of these communities are affected by the surge in truck traffic and resultant air pollution. Exposure to diesel truck traffic is associated with health problems, including asthma, respiratory diseases, lung cancer, birth defects, and cognitive impairment; children are especially vulnerable (Reichmuth 2019). Diesel vehicles are the major source of highway PM emissions, like PM-2.5, and more than 50% of these emissions are from diesel heavy vehicles (Davis and Boundy 2021).

Signposts. Several interactive maps are available to screen for environmental and demographic information in the United States. These tools can identify areas disproportionately burdened by health and environmental impacts. These include the following:

- EV Charging Justice40 Map: A tool from Argonne National Laboratory providing interactive maps of communities made disadvantaged and public charging stations (Argonne National Laboratory n.d.).
- EPA EJScreen: Environmental Justice Screening and Mapping Tool. Diesel PM is an environmental indicator representing emissions from autos, trucks, and heavy on-road and off-road equipment powered by diesel fuel.

Likelihood. Absent major policy interventions, the proportion of truck emissions will likely increase in the coming decades (Lathwal et al. 2022). If no major efforts are made, there is a high likelihood that communities made disadvantaged will continue bearing the brunt of the ill effects.

Consequences. Overburdened communities exposed to transportation emissions could continue to experience adverse health effects due to the failure to integrate environmental justice into the decarbonization of the transportation sector. The nature of this hazard has implications for agency goals related to public health as well.

Mitigating Actions. Adoption of zero-emission MD and HD trucks can improve local air quality and reduce GHG emissions in overburdened areas with logistic and transportation activities (Tong et al. 2021). State and federal DOTs and MPOs can prioritize deployment of zero-emission MD and HD vehicles in these overburdened communities. This may require different types of infrastructure such as hydrogen, depot charging, and so forth. State and federal DOTs and MPOs can also work with state air quality or energy departments to address regulations around logistic activities. For example, Southern California air quality officials have adopted the Warehouse Indirect Source Rule (SCAQMD Rule 2305) in May 2021. This rule requires warehouses to invest in zero-emission trucks, charging or alternative fueling stations, on-site renewable energy, or other mitigation strategies.

Gaps in Knowledge. Most of the literature discusses potentials and pathways to zero-emission HD and MD trucks. However, implementation of truck decarbonization and infrastructure investment has not been undertaken.

Electricity Rate and Affordability of Charging

Rising utility costs will place a disproportionate burden on low- to average-income households. Electric utilities can face significant challenges from rapid integration of EVs, including securing adequate supply to meet the demand, preventing overload of system components, balancing phase and voltage, reliability, and stability (Das et al. 2020). Unregulated EV charging and the increased use of direct current (DC) fast charging can add more load during peak hours and can potentially affect the grid as well as require a large and expensive network upgrade (Smart Electric Power Alliance 2017; Allen et al. 2017). Utilities use rate design to recover costs or influence customers' behavior. Increased electricity costs will adversely affect communities made disadvantaged and will make EV charging more expensive.

Signposts. Potential signposts of this hazard were not found in the literature but could include the electricity cost burden for DACs and increases in rates.

Likelihood. There is a high level of uncertainty about EV adoption and eventual influence on electricity rates (Blonsky et al. 2019). The literature discusses the decarbonization of energy supply and technology development, but it does not specifically address the impacts these have on electricity rates in DACs. This area represents an area for further research.

Consequences. Electrification of transportation is expected to have the largest effect on electricity demand in the near future, and modified or increased electricity rates could increase the burden for low- and average-income households (Blonsky et al. 2019).

Mitigating Actions. An effective electric power management system and integrated energy planning can mitigate an overburdened grid or network. To mitigate the high impact on electricity rates, collaboration and coordination between utility companies, state Energy Commissions, DOTs, and developers are critical. Using smart technology such as managed charging or smart charging management systems (SCMS) can minimize stress on the grid. When done at a system-wide level, they provide additional system benefits like peak shaving, voltage control, frequency regulation, renewable integration support, demand-side management, demand charge reduction, loss reduction, and emergency demand response (Bhusal et al. 2021). State and federal DOTs and MPOs can work with state and federal energy departments to address regulations around charging station integration. For example, California AB 1100 and SB 676 require using SCMS to better integrate vehicles into the grid. However, integration with infrastructure and planning must be in place to realize improvements in interconnection processes. In addition, California AB 2127 requires the Energy Commission to work with the State Air Resources Board and the Public Utilities Commission to perform a statewide assessment of the electric vehicle charging infrastructure needs biennially and seek data and input from stakeholders regularly (Alexander et al. 2021).

Gaps in Knowledge. There are gaps in the literature surrounding the effects of EVs on electricity rates and their likelihood of occurring.

Agency Goal: Public Acceptance

The acceptability of the technology can determine its wider adoption by consumers in the larger transportation market. A review of the psychological factors influencing the public acceptance of clean energy technologies defines two types of public acceptance: (1) citizen acceptance, or the behavioral response to technologies managed or owned by others, such as nuclear powerplants; and (2) consumer acceptance, or the behavioral responses to technologies and related services available for public consumption, such as PEVs or charging stations (Huijts et al. 2012). The same study defines acceptability as an attitude toward a technology. For certain technologies, individuals can "base their acceptance on (1) the overall evaluation of costs, risks, and benefits, (2) moral evaluations, depending on the extent to which the technology has a more positive or negative effect on the environment or society, and (3) on positive or negative feelings related to the technology, such as feelings of satisfaction, joy, fear, or anger" (Huijts et al. 2012). Public acceptance may also be influenced by the technology's implementation, its location, and the intended consumer. Acceptance may include trust, procedural fairness, and distributive fairness according to different psychological theories (Huijts et al. 2012).

Huijts et al. (2012), upon reviewing studies of attitudes related to the use of clean fuel vehicles conducted by Altmann et al. (2003) and Molin et al. (2007), noted that vehicle price and performance "were the most important attributes influencing the preference for a vehicle." As DOTs and MPOs evaluate the risks that threaten agency public acceptance goals, the following hazards should be considered.

Perceived and Realized Barriers for Public Charging Stations

EV drivers experience barriers to accessing public charging infrastructure and services. The California Air Resources Board (CARB) conducted surveys of drivers. Membership requirements, unavailable or inoperable chargers, high prices, and payment issues ranked among the top barriers to entry for new EV drivers (California Air Resources Board 2022a). Membership to charging service providers was rated the highest barrier to public charging among drivers with 62% of drivers in California having memberships to two to five charging network service providers. The study argued that this could be a perceived barrier to EV adoption; California AB 1424 Electric Vehicle Charging Stations Open Access Act (Open Access Act) prohibits exclusive membership or a subscription fee to help provide publicly accessible payment options for chargers.

Another major concern is the payment option used by charging stations (California Air Resources Board 2022a). The predominant method of payment requires contactless tap technology for credit cards or applications for smart phones or other devices. Consumers have varying levels of access to traditional banking, and evolving payment technologies can hinder acceptance for consumers who are unbanked or have limited access to digital devices and services.

Signposts. Feedback from consumers has already proven valuable for reporting barriers to entry. Should this feedback continue to deliver similar findings, this could be a signal to reevaluate the current policies or could help assess the effectivity of previous mitigating policies. These surveys can also highlight new barriers. Additionally, monitoring payment technology implemented for charging stations and adoption of such technologies by demographic level can provide insights into disproportionate access barriers.

Likelihood. Surveys have already identified issues as barriers to entry for new EV drivers, but this hazard may evolve as EVs, EVSE, and payment technologies evolve. These issues are most likely to occur in the first half of the technology adoption cycle—among innovators, early adopters, and the early majority.

Consequences. The barriers reported suggest there is a risk of underutilization of public charging stations. Issues related to payment options, or lack thereof, may also have implications for equitable access to these services by underserved communities and thus also affect agency equity goals. Because EVs are seen as an easy pathway toward reducing transportation GHGs, acceptance risks by nature also have implications for agency goals related to sustainability and climate change.

Mitigating Actions. Surveying and soliciting monitoring drivers' feedback can be useful. EVSE access dashboard is recommended by CARB to track public charging market trends and utilization trends of charging stations (California Air Resources Board 2022a).

EVSE standards should ensure that EV charging is easy, reliable, and available to all. The Open Access Act can be adopted widely to prohibit exclusive memberships or subscriptions to access public charging infrastructure. Available payment options should pace with technology adoption, approximately 15% of Visa credit cards are tap-enabled today, and penetration is expected to be low for the next 2 years (California Air Resources Board 2022a). Therefore, charging service providers should not assume their consumers will have access to these payment options in the near term.

Gaps in Knowledge. There is little understanding of how low-income residents would pay for transportation services and public EV charging when payment technologies are quickly evolving.

Delays to Charging Station Buildouts

The scale of required charging stations to support EV adoption illustrates the risks to EV acceptability. The amount of public charging that will be needed to facilitate widespread EV adoption has been studied in Sweden and Norway, which currently have high levels of EV adoption. Using real-world, fast charging data, a model was created to determine the ideal ratio of battery EVs to rapid public charging points. This study concluded that the ideal ratio of fast charging points per 1,000 vehicles could be close to the current number of refueling stations for conventional ICE vehicles over time (Gnann et al. 2018). A separate study of 356 Norwegian municipalities between 2009 and 2019 found that the deployment of public charging infrastructure increases BEV uptake by more than 200% after 5 years (Schulz and Rode 2021).

Denser urban areas that have a greater proportion of on-street and large commercial garage parking will see an increased demand for public charging (Engel et al. 2018). To support an expanding electric vehicle market, the International Council on Clean Transportation estimates that approximately 1 million chargers will be needed at multiunit dwellings within the United States, with proportionally greater increases needed in rural areas and across the Midwest and South. They also estimate that at least 30% of chargers and charging investments through 2030 should be directed to lower-income communities to support equitable infrastructure access. Charging investments for public workplace chargers from 2021 to 2030 are estimated to cost approximately $28 billion (Basuer et al. 2021). They estimate that, of the total number of chargers, 7% would be DCFC (direct current fast charging) which will provide 57% of charging energy. However, while making up a small proportion of total charging infrastructure, DCFC would make up 66% of the total estimated cost, demonstrating the need to install inexpensive home and workplace Level 1 and Level 2 charging as well (Basuer et al. 2021).

Challenges in EV charging station buildouts can include complex utility interconnections, permitting incongruities, and low EV adoption rates. Current utility interconnection processes are nontransparent, and their costs and timelines are varied and unpredictable (Nelder and Rogers 2019). This creates challenges for charging station installers because they are unable to estimate the time, the availability of needed grid capacity, and the cost of required grid upgrades. Building codes and permitting processes vary by local jurisdictions, requiring significant resources to obtain permits and make design modifications. (Nelder and Rogers 2019).

The pace of EV adoption has been increasing steadily. In the United States, around 250,000 to 300,000 units were registered annually in 2018, 2019, and 2020, representing about 2% of sales (International Energy Agency 2021). The National Electric Highway Coalition estimates the United States will need 100,000 fast charging stations to support the 22 million EVs they estimate will be on the road by 2030 (Edison Electric Institute 2021). The U.S. needs for public charging infrastructure buildout are likely to follow demand from jurisdictions with higher levels of ownership.

Signposts. Indicators of charging infrastructure delays could include (1) lead time for charging station development to complete and (2) differing EV adoption rates in neighboring areas.

Likelihood. Challenges have been recognized by industry, and staff at the California Energy Commission argue that permit delays could affect the state's ability to meet its EV targets (McCarthy 2021). Therefore, there is a high likelihood of this hazard having influence on agency goals. This hazard is more likely to occur in the early part of the technology adoption cycle as charging infrastructure is still under construction.

Mitigating Actions. Technological improvement, government policy, city planning, and power utilities all play a role in development of charging infrastructure (International Energy Agency 2021).

California streamlined the permitting and interconnection process with AB 1236 and Rule 21. In response to AB 1236, a permitting guidebook was published. It includes an optimal permitting process, current restrictions, and information on permit ready local jurisdictions (Nelder and Rogers 2019). Despite the state's effort to streamline the permitting process, only about one-quarter of the jurisdictions in the state currently comply with the provisions (McCarthy 2021). Similarly, Rule 21 is a comprehensive standard policy for an accelerated and streamlined interconnection process for rooftop solar integration. This approach could provide valuable lessons for EV charging interconnection challenges. However, multiple Level 2 chargers or DCFC and MD and HD vehicle fast charging represent much larger capacity than rooftop solar, and it could be an order of magnitude more challenging to expedite or streamline the interconnection process (Trabish 2019).

Hosting utilities can also help streamline the permitting process by increasing transparency within their organizations. Having transparency on the available capacity of a distribution system to a prospective site (i.e., hosting-capacity maps), increasing communication and designating a single point of contact, and identifying upcoming EV service provider projects in nearby locations can help in this process.

Local jurisdictions can provide guidance on requirements and the process for a building permit, and state or federal agencies can standardize processes and specifications.

Gaps in Knowledge. Most of the literature discusses potentials and pathways to zero-emission HD and MD trucks. However, implementation of truck decarbonization and infrastructure investment is still not well understood.

Electricity Rate and Affordability of Charging

Rising utility costs may affect the acceptability of EVs, especially among communities made disadvantaged. However, a deeper discussion of this hazard is best suited within the section on equity concerns.

Agency Goal: Safety

Safety hazards associated with EVs and charging infrastructures can emerge due to lack of regulatory oversight, technology failure, human factors, and other reasons. Electric shocks and fires are safety risks of EVs. These risks also include fall and trip hazards.

Two major hazards identified in the literature are described in detail: (1) new charging technologies and (2) battery fire and explosion.

New Charging Technologies Entering the Market

Different needs for charging will likely evolve as more of the transportation sector is electrified and new technologies enter the market. Further innovations in technology can support meeting the transportation electrification goals. Charging technologies that have recently entered the market include overhead pantograph chargers for electric buses and HD trucks, mobile chargers for flexible geographic demands, inducive charging to eliminate cords and wiring, and EVSE operating at 350 kW or more for charging time reduction (Chang and Kalawsky 2020). New technology deployment can come with unknown safety risks to workers and users. There are several technology innovations underway, such as vehicle-to-grid, that may outpace the regulatory timeframe that could create safety risks for workers and users in the future.

Signposts. Surveys of consumers and employees working at charging stations can be informative as can investigations by federal agencies like the Occupational Safety and Health Administration (OSHA), NTSB, and NHTSA. If these agencies pursue investigations into incidents linked to charging, they could provide a signpost to alert transportation agencies to this hazard.

Likelihood. Due to the necessity of charging infrastructure for the deployment of EVs, there is a high likelihood that new charging station technologies could influence the safety of consumers and workers unfamiliar with the equipment. Because of the nature of the deployment of charging infrastructure in the near term, it is likely that the highest risk of this hazard exists in the early half of the technology adoption cycle (i.e., to innovators, early adopters, and early majority consumers).

Consequences. With advances in charging technology, new and sometimes unexpected risks come to fruition. Although wireless charging technologies could eliminate a target of vandalism (e.g., cutting charger cables) and some safety hazards of wired EVSE, like trip and fall hazards, they also present new concerns. Improperly installed or maintained charging stations can be a safety hazard if workers are not properly trained. Wireless charging for EVs requires high outputs of electrical power (increasing the probability of fires and electric shock) and a large area to support power transmission via microwaves, which increases exposure to electromagnetic fields.

There is also the potential for natural disasters to affect the safe operation of EVSE postincident. As transportation is more electrified, mobility of people and goods is more dependent on the power system as their fuel source. Climate hazards such as sea-level rise, extreme weather events, and wildfires interrupt, damage, and destroy power delivery infrastructure or services (U.S. DOE 2016). When EVs are adopted at scale, short- or long-term power outages or power price shocks will have implications on mobility. Potential impacts on mobility and economies from climate-driven power service interruptions are uncertain and hard to predict. Climate-induced disruptions are already happening and will likely be increasing. Mobility resiliency must be thought out as more transportation is electrified.

Mitigating Actions. The California Public Utilities Commission issued a decision (California Public Utilities Commission 2020) that offers strategies for emerging transportation electrification technologies by creating a program and establishing an iterative process. The emerging technology program will facilitate laboratory testing, development of testing standards, paper studies, and small-scale field trials. The iterative process will include examining and enhancing the safety requirements and best practices that can advance vehicle grid integration technology and other emerging technologies (California Public Utilities Commission 2020). California Public Utilities Commission's decision emphasizes that identifying special safety requirements is needed for testing precommercial technologies as those technologies do not meet the existing safety standard or certification.

The NEVI Formula Guideline and BIL require states to consider resilience for operation during emergencies and extreme weather in their Strategic Deployment of EV Charging Infrastructure (FHWA 2022b). Some of the examples assess the vulnerability and risk of the potential climate change impacts for the EV charging stations, including flood risk, and consider opportunities to add redundance and improve resilience.

Gaps in Knowledge. There are gaps in the literature surrounding the effect of new charging technologies on safety and the likelihood of these risks.

Battery Fire and Explosion

Li-ion batteries exhibit a high energy density and pose a safety risk due to the possibility of manufacturing defects that may contribute to fires and explosions for both collision and non-collision incidents (Aalund et al. 2021). The consequences of this hazard can include electric shock, thermal runaway, and stranded energy (NTSB 2020).

Battery packs are made up of individual battery cells which are themselves composed of three major subcomponents: (1) electrodes which store electrochemical energy (anodes and cathodes); (2) separators which keep anodes and cathodes from making physical contact; and (3) a liquid electrolyte which allows the movement of chemical ions between the two electrodes (Yoshio et al. 2009). The dominant chemistry used in modern EVs is the lithium-ion battery. In a lithium-ion battery cell, an anode stores lithium ions while the battery is charged, and the cathode stores those ions when discharged. The separator is usually a polymer material dividing the two electrodes and preventing electrical shorts, allowing safe operation. Lithium-ion batteries replaced the nickel-metal hydride batteries used in the 1990s because they have increased energy density ($k \cdot Wh\ g^{-1}$), which lowered the weight of batteries and simultaneously increased vehicle range. However, that increase in energy density has an increased fire risk. The liquid electrolyte used in lithium-ion batteries is flammable when exposed to air or when exposed to an electrical short. This could cause thermal runaway, which can lead to a larger fire. "When a Li-ion battery [has been] exposed to an external impact [or] experienced extreme operating conditions, it can break, eject sparks, flammable gases and toxic smokes which can be further ignited and lead to steady combustion, jet flames or a gas explosion" (Sun et al. 2020). Batteries can also reignite after a fire has been put out if there is stranded energy left in the battery pack. Stranded energy is left-over energy stored in the batteries that is not dissipated by the fire (NTSB 2020).

As a result, a new class of lithium-ion batteries called solid state lithium-ion batteries are poised to deliver improvements not only in energy density but also in safety. Solid state lithium-ion batteries replace the flammable, liquid electrolytes used in current designs with solid electrolytes that are not flammable. Coupled with new anode chemistry that increases energy density, solid state lithium-ion batteries have the potential to increase EV range and dramatically improve safety.

Another technology relevant to battery safety is the battery management system (BMS), which is a suite of sensors and software used to collect and manage data about the battery's current, voltage, temperature, and other factors to allow safe operation and monitoring of the battery's characteristics such as state of charge, longevity, and others. Should a BMS become compromised, the safe charge and discharge of the battery pack cannot be guaranteed. For example, there are cybersecurity risks in EVSE and BMS that could result in overcharging the battery pack. These issues are described in the Security and Privacy section. BMSs are also expected to improve with the application of artificial intelligence and machine-learning algorithms to optimize battery pack performance and safety.

Signposts. When battery failures result in fires or explosions, a certain number of incidents will reach a threshold that will result in an NHTSA investigation, which can also lead to an EV automaker issuing a recall. This was the case for Hyundai and GM (Aalund et al. 2021). These recalls can act as signposts or red flags for federal and state DOTs or MPOs that EVs traveling on roads and highways, or parked in public spaces, may be at risk of fires or explosion.

Likelihood. Though this risk is acknowledged, and incidents have been investigated by the NHTSA and NTSB, the likelihood of an EV fire or explosion is no greater than that of

ICE-powered vehicles (O'Malley et al. 2015). Another study found that, due to the low market share of EVs, there was not enough data to make a fair comparison with ICE-powered vehicles (Sun et al. 2020). Additionally, the heat released by an EV is comparable to ICE-powered vehicles (Sun et al. 2020).

Because part of this hazard can be related to the manufacturing process, it is likely to improve over time as original equipment manufacturers (OEMs) seek out better suppliers and suppliers themselves improve their quality assurance (QA) processes. The other part of this hazard results from the ability and knowledge of first responders to put out EV fires when they occur from collisions. Given these factors, the risk of lithium-ion battery fires and explosions is likely to be greatest during the first half of the technology adoption cycle—when innovators, early adopters, and the early majority increase the demand pressure on OEMs trying to scale their operations and when fire departments and other first responders are still learning how to treat EV fires. However, risks of fires and explosions remain due to cybersecurity-enabled overcharging hazards as explained in the Security and Privacy section.

Consequences. Extinguishing an EV fire is different from extinguishing an ICE fire. Though there are a variety of studies focused on best practices for responding to lithium-ion batteries and EV fires (Park et al. 2013; Wang et al. 2019; Kong et al. 2018), there also needs to be a consolidated effort to educate first responders with this information. A small study by the NTSB (2020) indicated that 50% of fire departments in a survey reported being unprepared for EV fires. NTSB (2020) found there was "inadequacy of vehicle manufacturers' emergency response guides for minimizing the risks to first and second responders posed by high-voltage lithium-ion battery fires in electric vehicles." Though the risk of fire or explosions is no greater than that of conventional vehicles, potential consequences from fires spreading to other vehicles and buildings may vary with the location of the charging station; if the fire is within an underground parking structure, for example, the result could be severe property damage or injuries.

Mitigating Actions. The root cause of noncollision fires or explosions may be related to problems in the manufacturing environment (Aalund et al. 2021). Battery failures resulting from OEM problems limit the ability of DOTs and MPOs to mitigate part of this hazard. However, agencies can still assist NHTSA or any other investigative body whenever an incident occurs on public infrastructure. Other organizations working to develop and implement safety standards like the American National Standards Institute, SAE, OSHA, Nationally Recognized Testing Laboratories, and others can also provide useful guidance on EV and EVSE safety standards (Kettles 2015).

To help educate first responders, OEMs can make fire response clearer and standardized across the industry (NTSB 2020).

Gaps in Knowledge. There are still gaps in the amount of data collected from EV fires and appropriate responses.

Agency Goal: Security and Privacy

Because PEVs are dependent on charging systems connected to the wider electrical grid, communication systems, payment systems, and other infrastructure, they present a unique set of challenges to ensuring a robust cybersecurity network. Current vehicles powered by internal combustion engines already demonstrate a variety of cybersecurity vulnerabilities and issues; however, this literature review of cybersecurity hazards will only focus on those unique to EVs.

Successful Hack of Charging Stations or EVs

There are several cybersecurity vulnerabilities to EVs, EVSE, and the grid. These include "man-in-the-middle attack, data integrity attack, payment fraud, privacy/tracking concerns, [malicious] charging or discharging, denial-of-service attack, malware injection with the help of PEVs, and rapid cycling of a large number of PEVs are potential attacks on [smart charging management systems (SCMS)] and its integrated components." Cyberattacks can result in effects in both the physical world and the information space. To prevent or mitigate risks, there are three cybersecurity objectives to meet in a cyberphysical system: (1) availability of the service, (2) integrity of the data and data exchange, and (3) confidentiality of the data transmissions (Gottumukkala 2019).

Signposts. Increased incidents of data theft, sudden unavailability of chargers and stations, and cyberattacks from EVSE or EVs can act as indicators of vulnerabilities in the vehicle-charger ecosystem.

Likelihood. The interconnected nature of EVs and the grid provides more surface area at risk of penetration by hackers. Studies into the cybersecurity of the power sector suggest that hackers already have been successful at penetrating systems connected to the grid and will likely continue to do so. Charging stations have already been hacked in several countries with a variety of outcomes. This includes displays of inappropriate material on screens, slowing or stopping EVSE from supplying charge, loading ransomware onto EVSE, and acquiring free service. Because payment systems and other communication systems are connected to the Internet, EVs and EVSE are more than likely to continue to be targeted by hackers.

Publicly available Level 2 EVSE have more complicated hardware than privately owned Level 1 or Level 2 chargers (Gottumukkala 2019). This is because they require communications packages for a wired or wireless (e.g., Wi-Fi, Bluetooth, cellular) interface. Level 3 chargers are much the same. This hazard is therefore more likely to occur in Levels 2 and 3 chargers that are open to the public.

Consequences. The consequences of a hack of EVs or EVSE depend on the aim of the attack. Table 3.1 lists these consequences.

Table 3.1. Consequences of successful hacking of charging stations or EVs.

Cyberattack Type	Potential Consequences
False Data Injection Attack (FDIA)	— Overcharging PEV batteries leading to damage to the PEV and the grid.
Man-in-the-Middle (MITM) Attack	— Tracking issues, payment fraud, and violating other personal privacy. — Intentional overcharging/discharging of PEV batteries, causing damage to PEV and its batteries and taking the PEV out of service or degrading range. — Overload distribution transformers and sometimes power grid frequency and voltage stability disturbances leading to power grid failure via rapid cycling of a large number of PEV loads. — Other personal safety concerns.
Denial-of-Service (DOS) Attack	— Denial of charging services to customers and emergency responders.
Malware Injection	— Theft of payment information (e.g., debit/credit card information, payment amount), personal information, and charging information. — Potential for Malware to spread to a network of EVSE, PEVs, SCMS, and the power grid using EVSE or PEVs as vectors for infection.

Source: Bhusal et al. (2021, 1–6).

Mitigating Actions. A critical component of risk mitigation against cybersecurity is detection of an attack. By instituting detection algorithms, FDIA and MITM and DOS attacks could be more quickly responded to and ended (Bhusal et al. 2021). The charging station industry would need to be responsible for installing detection algorithms in charging stations and automakers would be responsible for PEVs. Industry would also need to follow any standards set forth by government entities like NHTSA, SAE, and National Institute of Standards and Technology (NIST) (Gottumukkala 2019). Detection algorithms will not lower the exposure of infrastructure and vehicles to cyberattacks, but they can help reduce the scale of a hazard's impacts and the length of time those impacts are endured.

An effective way to ensure robust charging infrastructure is to perform cybersecurity testing and assessments during installation (Bhusal et al. 2021). Industry partners and third parties would be responsible for testing EVSE.

Researchers at Sandia National Labs also present security protections for EV charging technologies (Johnson et al. 2022).

Gaps in Knowledge. Because charging infrastructure in the United States is still deploying, several gaps in knowledge are contributing to privacy and cybersecurity risks. Cybersecurity best practices have yet to be established and remain immature. This has the added effect of limiting the amount of cybersecurity standards applicable to end-to-end communications between PEVs, EVSE, and the power grid. Some standards are still in the development phase. There are also limited services available to perform cybersecurity-related testing and assessment at charging stations and for PEVs. Finally, there are limited guidelines and guidance on physical security and cybersecurity requirements. Cybersecurity for wireless charging infrastructures is still in the testing and demonstration phase (Bhusal et al. 2021).

Agency Goal: Sustainability and Environment

In 2019, the transportation sector was the largest contributor to U.S. GHG emissions accounting for nearly 30% of the total. Of the 30%, other sources (like on-road vehicles, including passenger cars, trucks, buses, and motorcycles) accounted for three-quarters (U.S. EPA 2021).

An Intergovernmental Panel on Climate Change study reported that fuel switching is a relatively easy path for transportation GHG reduction compared to other options that would likely require behavioral or social changes. Replacing ICE vehicles with PEVs has the potential for both short-term and long-term GHG reduction. The report discusses opportunities and barriers to EV adoption. Opportunities included universal standards for EV chargers; expanding charging infrastructure; decarbonizing electricity generation; establishing smart grids based on renewables; and new business models such as community car sharing. Barriers included the cost of EVs and batteries (although their costs have consistently fallen over time, they remain relatively high compared to ICE vehicles); lack of charging infrastructure; suffering from ununiform recharging standards; and vehicle range anxiety.

The following hazards pose risks to those transportation agency goals related to sustainability and climate change.

Failure to Meet GHG Reductions with EV Adoption

Several factors are challenging the ability of transportation agencies to meet GHG reduction goals and "even with the recent success of EV deployment, reaching a trajectory consistent with climate goals is a formidable challenge" (International Energy Agency 2021). A few factors are highlighted as follows.

MD and HD trucks are responsible for 24% of transportation GHG emissions (U.S. EPA 2021); however, not all MD and HD vehicles will be suitable for electrification as technical, economical, and operational feasibilities are critical for successful adoption (Burke and Sinha 2020). Short-haul operations (≤ 200 miles) and transit buses have more opportunities to be electrified given their short and predictable routes and return-to-base applications, which allow the vehicle to recharge after a shift (Borlaug et al. 2021; International Energy Agency 2009).

Because of the interconnected nature of the charging and energy infrastructure, it is more difficult to track GHG emissions from an electric vehicle fleet because the emissions originate upstream (Richard 2014). As EVs supplant ICE vehicle fleets around the world, an increase in electricity usage from utilities is expected. According to some estimates, electricity's share of final energy could double by 2050 and 76% of all vehicle miles traveled (VMT) could come from electric drivetrains (Murphy et al. 2020). In such a scenario, the ubiquitous adoption of EVs may mar the ability of researchers to monitor GHG emissions due to the difficulty in tracing a vehicle's source of electricity generation. The location of the charger and the time of day consumers charge their EVs affect where electricity is sourced from. Utilities could be burning natural gas or coal, or they could be sourced from cleaner technologies like hydroelectric, solar, or wind. All these factors affect the carbon footprint of the electricity generated.

Charging stations may also make it more difficult for organizations to meet their own sustainability goals. When an organization decides to install charging infrastructure in their place of business, they become the demand signal for electricity generation (Richard 2014). This means the host of the charging station becomes the owner of the emissions rather than the drivers plugging in their EVs.

The transition to EVs as a strategy to reduce emissions also assumes a transition to more renewable energy to power EV chargers (International Energy Agency 2021). As of 2020, renewable energy in the United States makes up approximately 12% of total energy consumption. Of the 12% used for renewable energy, approximately 39% of the energy is acquired from biomass (biomass waste, biofuels, and wood) (Energy Information Administration 2021). The proportion of renewable energy is generally expected to increase over time but may vary significantly by state within the United States, with some states legislating emissions reductions over time and others with no legislative mandates on energy composition.

It is possible that charging infrastructure supporting other emerging transportation technologies (i.e., CAV, MOD/MaaS) may increase VMT. As these new technologies arrive in the market, they may spur demand and will increase emissions overall.

Last, the transition to EVs necessitates the procurement of the raw materials needed to support the industrial base in its pursuit of production. There are concerns that the transition will cause more mining and processing capacity to be built out, increasing GHG emissions. There are also concerns about sourcing materials, mainly cobalt, from war-torn areas like the Democratic Republic of the Congo.

Signposts. Monthly and annual EV sales, new vehicle registrations, and kWh deployed can all account for the replacement of ICE vehicles with EVs. Should DOTs hold internal goals to convert organizational fleets to EVs, these metrics could also help monitor the progress of the transition.

Likelihood. The International Energy Agency's Global EV Outlook report, released annually, presents two future scenarios using projections of global EV stocks based on two inputs: (1) the policies needed to achieve carbon reductions to limit the effects of climate change and global warming called the Sustainable Development Scenario, and (2) polices that have been stated by governments called the Stated Policies Scenario. The Stated Policies Scenario projects global

EV stocks totaling 145 million by 2030, while the Sustainable Development Scenario projects 230 million EVs needed to meet GHG reduction goals (International Energy Agency 2021, 74–75). Likely, EVs will not meet the numbers needed to limit the rise in global temperatures. Whether or not governments will meet their stated goals is another matter.

Consequences. This risk of missing GHG reduction targets is tied to rising temperatures, which is well-documented and will not be reproduced here.

Mitigating Actions. "In the short term, countries can continue to implement, enforce, and tighten measures such as CO_2 and fuel economy standards and EV mandates. Taxing gasoline and diesel at rates that reflect their environmental and human health impacts can provide government revenue, reduce their negative impacts, and hasten the transition to electric mobility. Differentiated taxation of vehicles and fuels that reflect their environmental performance can further align markets with the climate benefits of EVs" (International Energy Agency 2021). States have implemented various policies to mitigate the effects of climate change. Statewide GHG reduction goals are established through executive actions or binding statutory requirements. Several states also participate in the Transportation and Climate Initiative (2020) to reduce transportation-sector emissions more specifically.

The electrification of MD and HD vehicles is paramount to meeting GHG emission targets (International Energy Agency 2021). State and federal DOTs can aid in charging infrastructure buildout to support MD and HD PEV deployment. This can be accomplished via tax incentives, carbon credits, and mandatory implementation of zero-emission HD vehicles. Most electrification efforts are focused on shorter-haul applications due to range limitations and favorable total cost of ownership (California Air Resources Board 2021). Hydrogen fuel cell technologies could potentially be viable for long-haul operations and other fleets with unique challenges to electrification (e.g., crane trucks, logging trucks, and emergency trucks).

The technology exists to recycle these components and generate raw material sources for industry (Velázquez-Martínez et al. 2019). However, in the United States, recycling capacity is generally low and limited to commercial ventures and research at national laboratories. In contrast, the European Union requires automakers to guarantee recycling of lithium-ion batteries (LeBeau 2021; Malooley 2021).

The charging infrastructure required to support taxis, MOD/MaaS providers such as Uber or Lyft, and other such fleets with high circulation warrants special consideration. The State of Oregon conducted modeling to understand the particular charging needs of ridehail vehicles. Their model analyzes charging needs according to local VMT data and identifies a vehicle-to-charging port ratio that can be applied according to local VMT data elsewhere (Kittelson & Associates, Inc. 2021).

Gaps in Knowledge. Gasoline and diesel fuel have more consistent carbon intensity, which makes it easier to calculate emissions for ICE vehicles compared to EVs. This uncertainty concerning EVs may be challenging for researchers who try to model emissions and progress toward reduction goals.

With the increased demand for EVs driving production, questions about sustainability of the supply chain arise. A single EV requires thousands of individual battery cells in every pack. Each cell contains electrodes, liquid electrolytes, and metals (e.g., iron, nickel, cobalt, aluminum, copper). Extracting these minerals and processing them into value added chemicals emits GHGs. Although there is an overall reduction in GHG emissions when comparing lifecycle assessments of EVs and ICE-powered vehicles, about 20% to 30% (International Energy Agency 2021), it is difficult to measure the difference in environmental benefits between battery technologies. High energy density materials may increase the range of vehicles and thus reduce emissions from electricity generation. Low energy density materials may be easier to process and produce fewer emissions during production (Reuter 2016). Additional methodologies for studying battery supply chain emissions are needed.

Agency Goal: Internal—Budget

As EVs take to the roads, they will affect the revenue streams of not only OEMs but also the state and federal DOTs' sources of funding like the motor fuel excise tax (MFT). Depleting revenues will decrease these organizations' ability to effectively care for and build new highway infrastructure and other responsibilities. The following hazard relates to the departmental budgets.

Declining Highway Trust Fund (HTF) Revenue from Increasing EV Adoption Rates

MFTs fund a substantial portion of the improvement and maintenance of the nation's transportation infrastructure at the federal, state, and local levels (Hardman 2021). The existing motor fuel tax system is challenged with increasing expenditures and declining revenues due to various factors (Schroeder 2015). At the national level, the HTF is the main source of federal funding used by state governments to resource surface transportation infrastructure. The HTF is underfunded despite substantial fuel consumption increases over the past 30 years due to increasingly efficient vehicle technologies and taxes not increasing with inflation to the point that Congress now regularly transfers general funds to keep it solvent (Kirk et al. 2021). The Infrastructure and Jobs Act secures the HTF spending authority until October 2026 and transfers $90 billion to the highway account; however, it does not address the continuing gap in funding (Cantwell 2022). States and some local municipalities also collect revenue from motor vehicle taxes for maintenance and improvement of surface infrastructure and have also been experiencing declining revenues over time.

These issues are likely to be exacerbated by the growth of the EV market (International Energy Agency 2021). BEV owners do not need to purchase traditional gasoline or diesel fuels, do not contribute to motor fuel taxes, and, therefore, do not contribute nearly as much as ICE vehicles to the maintenance and improvement of surface infrastructure. Without a mechanism to recuperate losses in revenue, the infrastructure resources will continue to decline.

In response, some states have started collecting higher fees from annual vehicle registrations and special tag or license plate fees for EVs. However, these schemes do not provide a funding mechanism proportional to driver use of public highways. In theory, an EV owner could pay a static fee while driving unlimited miles, which runs counter to the fee-user benefit model the HTF is based on (Short and Crownover 2021). Hence, underfunding may continue to be a long-term issue.

Signposts. Indicators of HTF and state revenue impacts from EVs could be determined from EV registration rates. Should registration rates meet or exceed projected numbers, revenues will likely continue to fall. The HTF has a minimum prudent amount set at $4 billion for the highway account that, if reached, necessitates cash management operations that slow down payments to states. If this threshold is reached, it could be an indicator of the impact of EVs at the federal level. However, it may be challenging to isolate EV impacts because transportation funding structures vary widely by state or local jurisdiction. Improved ICE vehicle mileage efficiencies and inflation further skew the impact as well (Schroeder 2015).

Likelihood. A study from the American Trucking Research Institute suggests that with national and state goals to lower carbon emissions, there is a likelihood of declines in MFT revenue in the future. In the near term (2021–2025,) the effect will remain minor but will increase as more EVs take to the road. Larger vehicles pay substantially more per mile fuel tax than smaller vehicles (Short and Murray 2021). The impacts will likely increase to moderate in the midterm (2025–2035) and major in the long term (2035–2050) as more models of MD and HD vehicles become available to consumers and fleet operators. However, each state will have a different rate of EV adoption and a proportionate impact on HTF revenue. This hazard has a higher impact as time progresses; the largest impacts will likely be felt during the late majority and latter portion of the technology adoption cycle.

Consequences. EVs are exempted from fuel tax in the current motor fuel tax system. While funding contributions from local, state, and federal fuel tax vary widely across jurisdictions (Schroeder 2015), MFTs are the major source of revenue for transportation infrastructure at all levels (Schroeder 2015). The revenue impact from increased EV adoption could be different for each state; however, mass adoption of EVs will have a negative impact on agencies' budgets. At the beginning of 2021, over 1 million PEVs were registered in the United States (Davis and Boundy 2021), which corresponds to an estimated $92.2 million in federal fuel tax losses for the HTF annually (Short and Murray 2021). Projections indicate that 18.7 to 19.6 million EVs will be on the road by 2030 in the United States (Edison Electric Institute and International Energy Agency), representing $1.2 billion in revenue losses to the HTF (Short and Murray 2021).

EVs are transportation system users and are responsible for paying their fair share of transportation infrastructure like any other traditional vehicle. Negative impacts on equity could be further exacerbated by inequitable EV ownership. Most EV owners have socioeconomic characteristics such as higher income, which, in the aggregate, could disproportionately spread the responsibility of supporting local infrastructure to taxpayers with lower incomes (Farkas 2018). Therefore, this hazard has implications for agencies' equity goals as well.

Mitigating Actions. To recuperate losses in revenue and distribute the tax burden more equitably, some states have already revised MFTs and have alternative tax schemes in place to supplement MTFs (Hartman and Shield 2020; Schroeder 2015).

VMT tax, road user charge, and mileage-base user fee refer to replacing the MFT with a tax based on the miles traveled by the driver. Such a scheme would distribute costs in proportion to road usage with differing rates still applicable to MD and HD vehicles. However, the feasibility of such a program is somewhat in question as the program would need access to vehicle mileage. This may result in extra equipment, or a device, installed on every vehicle by manufactures and may raise political resistance because of concerns over data privacy. A federal motor vehicle per mile user fee pilot program is to be conducted under the Infrastructure Investment and Jobs Act (IILA). It will also establish a Federal System Funding Alternative Advisory Board to assist the Secretary of Transportation with recommendations for implementing the pilot program.

Some states, such as Georgia, have high annual registration fees designed to recuperate losses in revenue. However, a loophole exists in that a driver could potentially pay a flat fee and have unlimited access to highway infrastructure. These high registration fees may also disincentivize EV adoption and are often paired with other incentives such as tax credits or rebates (Short and Murray 2021).

Another alternative is an electric fuel tax based on kWh used to charge an EV battery pack. However, implementation would be complex. The majority of EVs are charged at the owner's place of residence (Short and Murray 2021). To measure the kWh used for charging, utilities would need to monitor electricity consumption via smart meters as well as smart chargers installed in homes. Charging in a commercial setting would be easier to implement as Level 2 and Level 3 chargers require large enough amounts of power that dedicated meters are likely already installed and already measure energy consumption to tax the consumer appropriately (Short and Murray 2021). Such a system would be easy to apply to ICE vehicles as all that is needed is a simple conversion factor for gallons of fuel (Short and Crownover 2021).

Implementation of mitigating actions at the federal level requires an act of Congress. The adoption of the IIJA is a temporary solution keeping the HTF solvent, but long-term solutions are still needed.

There is more inconsistency in the ability to implement mitigating actions at the state level due to the various procedural responsibilities and differences among the states. For example, some states may require voters to approve new changes to the tax code while others give that responsibility to state legislatures.

Gaps in Knowledge. Numerous alternatives are proposed and tested at the state level. However, there are uncertain inconsistencies between states. These inconsistencies could result in potential double-counting or avoiding taxation from interstate travel.

Transportation funding shortfalls involve many other challenges. The need for infrastructure reform and improvements is significant and costs are increasing. It is unclear whether the taxation of alternative fuel vehicles can solve the greater issue of the nation's infrastructure funding shortfalls (Schroeder 2015).

Some of the tax structures being proposed are still gathering data on viability and optimization; success is not guaranteed. It is also unclear how new tax structures may influence equitable tax burdens.

Taxation of alternative fuel could have an impact on the adoption of EVs and high-efficiency vehicles. This could result in a potential negative impact on GHG reduction goals (Schroeder 2015). A robust funding solution that can balance parity across fuels and technologies, funding transportation infrastructure, and the reduction of petroleum consumption and vehicle emissions needs to be discussed.

EV Risk Register by Risk Priority

The risk register of potential sources of risk from EVs is in a pair of tables: Tables 3.2a and 3.2b. Table 3.2a provides information typically found in a standard risk register (while applying the exceptions discussed in Chapter 2). This table presents its rows in descending order of assessed risk priority. Table 3.2b provides data that underly the calculation of both forms of the LOC measure, the SI-LOC and CB-LOC (see Chapter 2). These data are useful for raising awareness within the agency of the relevant aspects of a source of risk from emerging and disruptive technologies to agency goals. Therefore, each pair of tables provides more detail than is typical of standard risk registers to present the underlying methodology so that agencies can make modifications that will support their own deliberations and risk prioritization. The full methodology for doing so is found in Appendix C.

The same data appearing in Tables 3.2a, 4.1a, 5.1a, and 6.1a are presented in Appendix B sorted by agency goal.

Tables 3.2a and 3.2b are followed by a review of the literature on potential hazards (sources of risk) connected with EVs.

Table 3.2a. Risk register by risk source (hazard) for EV technology group.

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
E1 Inequitable Payment System	Barriers to public charging station access due to payment options.	Contactless prepaid cash card adoption rate or track charging station payment options to understand the trend and options.	4	Equity	EV charging station payment option limiting certain users (e.g., unbanked, digital poverty, low credit score).	4	Establish or enhance the EVSE standards to ensure easy, reliable, and available access to all.	Federal and state DOTs and MPOs in collaboration with third-party survey providers.	**Extreme**
E2 Exposure to Emissions	Disproportionate exposure to transportation emissions.	1. Diesel PM and NO_2 air quality data paired with DAC (diesel index from Justice40 map). 2. Commercial zero-emission truck registration data. 3. Access to commercial vehicle charging stations.	3	Public Health/ Equity	Continuing or worsening adverse health effects for communities exposed to transportation emissions.	4	Prioritize deployment of zero-emission MD and HD vehicles in the overburdened communities and better understanding of infrastructure needs.[d]	State DOTs and MPOs in consultation with state environ-mental or energy departments and local jurisdictions.	**Extreme**
E3 Delayed Buildouts	Delays to charging station buildouts: 1. Permitting and interconnection process. 2. Grid constraints limit charging station buildout.	1. Lead time for charging station development to complete. 2. Differing EV adoption rates in neighboring jurisdictions indicated by EV registration data.	4	Sustainability	1. Delayed EV deployment and failure to meet the GHG reduction goals. 2. DACs lack charging Infrastructure.	3	Streamline and increase transparency for the permitting and interconnection process.[e]	State legislatures; hosting utilities; and federal and state agencies.	**Extreme**

E4 Hacking Charging Station	Successful hack of charging stations or EVs.	1. Increased incidents of data theft. 2. Number of cyberattacks by vehicle make, charging network, and payment systems.	3	Security and Privacy	1. Cyberattacks that could result in (a) Data theft and fraud. (b) Denial of charging services. (c) Malware spread.	**3**	1. Establish standards for automated and connected systems and technologies. 2. Strengthen system response and recovery plans.	Industry, government agencies.	**High**
E5 Fuel Tax Revenue Decline	Declining fuel tax revenue from increasing EV adoption rates.	1. EV registration rates. 2. HTF minimum prudent amount.	3	Internal—Budget	Expecting over $1B in revenue lost annually by 2030.	**3**	Design alternative tax schemes for EVs while considering consistency with neighboring states and equity.	State and federal DOTs; MPOs; state and federal legislatures.	**High**
E6 Unreliable Charging Service (Human)	Unreliable public charging service due to human behavior. 1. Fully charged EVs are not making space for other users. 2. EV-dedicated spaces are occupied, or conventionally fueled vehicles are parked in EV-dedicated spaces).	Customer feedback on reliability of service and wait time to get charged.	3	Mobility/ Public Acceptance	[Acceptance] Low acceptance for EV. [Mobility] Increased VMT to find available charging stations, increased wait time, compromised mobility.	**3**	Employ charging valet services for high-demand charging stations.	State DOTs and state agencies in collaboration with industry, charging station operations and maintenance, high-demand stations (e.g., airports).	**High**
E7 Battery Fire	Battery fire and explosion: 1. EV fires are more difficult to extinguish than ICVs. 2. EVs submerged or damaged from a storm have a potential risk of a high-voltage electrical battery fire.	1. NHTSA investigations related to battery safety. 2. Vehicle recalls related to battery. safety issues 3. EV fire by causes.	3	Safety	Though the risk of fire or explosions is no greater than that of conventional vehicles, there still exists the potential for fires to spread to other vehicles and buildings near the point of charge or crash.	**3**	1. Implement safety requirements and best practices for EVSE, battery packs, and BMSs. 2. Establish fire suppression system guidelines for higher-impact charging stations (i.e., underground parking structures).	NHTSA in consultation with federal and state DOTs, MPOs, and first responders.	**High**

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Table 3.2a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
E8 Inequitable Adoption	Inequitable EV adoption.	1. Access to charging stations (charger density compared to population density, geographical area, or population income level. 2. Drive times to nearest charger by low-income, urban, rural communities). 3. Justice40 metrics for measuring charging access for DAC. 4. Number or amount per application of EV rebate between DAC and non-DAC.	2	Equity	1. Inequitable distribution of benefits from a cleaner transportation and energy system. 2. High transportation cost burden for remaining ICV users due to disproportionate cost share of legacy infrastructures, unreliable fuel supply, and unaffordability of petroleum fuels.	4	1. Include equity in EV incentive design such as point-of-sale rebates, including used EVs, streamlining the application process, and reassessing eligibility criteria to a needs-based" approach (income, air quality, etc.). 2. Ensure equitable access to affordable and reliable charging stations.	State DOTs and MPOs work with state legislative and environ-mental agencies.	**Moderate-High**

E9 Unreliable Charging Service (Tech)	Unreliable public charging service due to technical issues and delayed service: 1. Improperly installed and maintained charging stations (i.e., insufficient cable length to accommodate certain vehicles). 2. Broken chargers, unresponsive or unavailable screen. 3. Lack of reporting or response system. 4. Insufficient workforce to respond to service requests.	1. Customer feedback on reliability of service. 2. Charger uptime. 3. Service lead time.	4	Mobility	Not getting the needed charge/user and worker injuries.		Establish charger reliability standards and service protocols, including communication systems, better training, prevention, and response safety technology/sensors, first responder training (electrocution), and notification.[f]	State DOT working with other state agencies and various stakeholders involved in Installation, operation, and maintenance.	**Moderate-High**
E10 Disparate Opportunity for EV Induced Jobs	Limited access to high-quality, clean transportation jobs in communities made disadvantaged.	Track clean energy job pipeline, job training, and enterprise creation in communities made disadvantaged for installing and maintaining EV charging infrastructure.	2	Equity/ Workforce	Inequitable access to economic opportunities and inequitable shift in the job market (i.e., high unemployment or job loss for traditional vehicle-supporting functions).	**3**	Forward-looking workforce planning policies, including equitable transition: 1. Early identification of trends in skills that may become in demand along with wider adoption of EVs. 2. Investment into workforce training and development, retraining programs for workers in the sectors displaced by EVs (i.e., mechanics). 3. Equitable workforce considerations.	Federal, state, and local DOTs, MPOs.	**Moderate-High**
E11 Insufficient Investment Decision Capability	Various technical expertise, staff capacity, and right-of-way policies across local jurisdictions' challenges on charging station deployment and EV technology.	EV charger utilization rates, charging station revenue, etc.	2	Internal—Budget/ Internal—Workforce	Public charging infrastructure becoming stranded assets (i.e., due to insufficient and unsustainable revenue from charging service).	**3**	1. Provide aid and support to state DOTs with fewer resources. 2. Provide data, guidelines, and tools that can be used for local agencies to support robust planning processes (i.e., Justice40 map, NAVI guidelines).	Federal DOT.	**Moderate-High**

(continued on next page)

Table 3.2a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
E12 Unaffordable Energy	Electricity rate and affordability of charging.	1. Energy cost burden for DACs. 2. Transporta-tion cost burden for DACs.	3	Equity	Modified or increased electricity rate increase burdens low- and average-income households.	**2**	1. Consider adopting a regulation for technology solutions to alleviate grid constraints such as power management systems like SCMS. 2. Integrate transportation electrification into grid infrastructure and resource planning.	State DOTs and MPOs in consultation with state energy department, and utilities.	**Moderate-High**
E13 Reduced Transit Service	Reduced affordable transportation options (e.g., less public transit, fare increase due to electrifying buses) due to investment and resource shift to electrification.	Commute time, no vehicle, or transportation costs for DAC (Justice40 map).	2	Equity	Reduced public resources in primary mobility modes for communities made disadvantaged.	**2**	Understand current state of the mobility burden and affordability of public transit for DACs and analyze the potential for reduced affordability due to vehicle electrification.	State DOT, MPO, and transit agencies.	**Moderate**
E14 New Charging Tech	New charging technologies entering the market.	1. Surveys of consumers and employees working at charging stations. 2. Investiga-tions by federal agencies like the OSHA, NTSB, and NHTSA.	2	Safety	1. Improperly installed or maintained charging stations. 2. Exposure to electromagnetic fields.	**2**	Establish a streamlined and adaptive process to facilitate safety requirements and best practices for emerging charging technologies in time.	State DOTs and MPOs in consultation with state energy agencies and electric utilities.	**Moderate**
E15 Exclusive Membership	Barriers to public charging station access due to exclusive membership requirements.	1. Consumer feedback and surveys. 2. Utilization rate per charging station, charging network, and membership requirement.	2	Mobility/ Public Acceptance	1. Underutilization of public charging stations. 2. More driving time to find the in-network charging options.	**2**	Establish or enhance the EVSE standards to ensure easy, reliable, and available access to all.	Federal and state DOTs and MPOs in collaboration with third-party service providers.	**Moderate**

E16 Low EV Adoption	Low EV adoption.	1. Monthly/ annual EV sales. 2. New vehicle registrations. 3. Carbon intensity of electricity.	1	Sustainability	Failure to meet GHG reduction targets.	**3**	1. Provide incentives to scrap older, high-polluting cars and replace them with zero-emission vehicles (ZEVs) (Clean Cars 4 All program in California). 2. Promote electrification of MD and HD[b] vehicles 3. Assess the projected charging need for daily charging, road trips, ride-hailing, MD and HD electrification, and off-road, port, and airport electrification.	State DOTs and MPOs collaborate with other state agencies (environ-ment, air quality, energy, etc.) and industry.	**Moderate**
E17 Grid Failure	Grid and network failure can have a cascading impact on EV mobility (i.e., extreme weather events, cybersecurity).	Evaluation of EV charging station resilience (hazards, vulnerability, redundant energy supply, etc.).	1	Mobility	Compromised mobility.	**2**	Assess vulnerability and consider resilience-improving measures (e.g., on-site generation and storage) for new and existing charging stations.	State DOT working with other state agencies and various stake-holders.	**Low**
E18 Lack of Supporting Functions	Lack of supporting functions to support EVs on the road and policy goals (e.g., ICV sales ban).	Projections and availability of supporting functions (e.g., number of EV technicians).	1	Mobility	1. Compromised mobility due to the lack of EV technicians, roadside assistance for battery depletion. 2. High unemployment or job loss for traditional vehicle-supporting functions.[g]	**2**	Funding allocation and program implementation in workforce retraining.[h]	State legislatures and state DOT in collaboration with other agencies.	**Low**
E19 Increased Crime	Increased crime around charging stations: 1. Overnight charging stations can be a target for vandalism.	Criminal stats by charger type (Level 2 vs. DCFC).	1	Safety	1. Compromised safety and security. 2. Increased vandalism.	**1**	Implement prevention measures and update codes and standards for charging stations (i.e., lighting, emergency phone, etc.).	DOT working with state and local jurisdictions.	**Low**

Table 3.2b. Elements of two likelihood proxies and overall results for EV technology group.

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Infor-mation	Response		Metric	Target	Tolerance Level (+/-)				
E1 Inequitable Payment System	2	4	3	2	3	4	1. Utilization rate vs. user socio-demographic information. 2. Unbanked and underbanked population density. 3. Payment/ membership equity score.	–	–	–	–	–	4
E2 Exposure to Emissions	2	4	3	3	3	4	1. NO_2 air quality data in DAC. 2. MD/HD ZEV deployment and charging stations.	1. EPA's 1-hour NO_2 standard at the level of 100 parts per billion (ppb) or an annual average of 53 ppb. 2. State goal of zero-emission MD/HD deployment.	Annual average of NO_2 less than 53 ppb or 1-hour NO_2 exceeding the standard more than twice a month on average.	Substantially out	Negative	3	3
E3 Delayed Buildouts	4	4	3	2	3	4	Lead time for onboarding charging stations, charging needs to support ZEV goal.	–	–	–	–	–	4
E4 Hacking Charging Station	4	2	3	3	3	3	–	–	–	–	–	–	3
E5 Fuel Tax Revenue Decline	2	2	3	1	3	3	Motor fuel tax per VMT vs. alternative fee/tax to EV per VMT.	–	–	–	–	–	3
E6 Unreliable Charging Service (Human)	4	2	4	2	4	3	–	–	–	–	–	–	3

E7 Battery Fire	2	2	3	2	3	3	EV fires should be monitored by cause and state (charging, parking, crash, driving, water immersion, etc.) to better understand their characteristics and establish a mitigation.[a]	—	—	—	—	—	3
E8 Inequitable Adoption	2	4	3	2	3	4	Annual approved EV rebates between DAC vs. non-DAC.[b]	50% meaning that the number of rebates from DAC are same as non-DAC.	40% to 50%	Substantially out	Positive	2	2
E9 Unreliable Charging Service (Tech)	2	4	1	1	3	4	—	—	—	—	—	—	4
E10 Disparate Opportunity for EV Induced Jobs	2	2	3	3	2	2	—	—	—	—	—	—	2
E11 Insufficient Investment Decision Capability	2	2	3	2	2	2	—	—	—	—	—	—	2
E12 Unafford-able Energy	4	2	3	3	3	3	Energy burden disparity between DAC and non-DAC from Justice40 map.[c]	—	—	—	—	—	3
E13 Reduced Transit Service	1	1	3	3	2	2	—	—	—	—	—	—	2
E14 New Charging Technology	3	2	1	3	2	2	—	—	—	—	—	—	2

(continued on next page)

Table 3.2b. (Continued).

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Infor-mation	Response		Metric	Target	Tolerance Level (+/-)				
E15 Exclusive Member-ship	2	4	1	2	2	2	1. Utilization rate vs. user socio-demographic information. 2. Public charging problems. 3. Payment/ membership equity score.	–	–	–	–	–	2
E16 Low EV Adoption	2	2	4	2	4	3	Cumulative EV sales in California: 1.3 M as of Q3/2022.	1.5M in 2022[d]	1.2M to 1.5M	On target	Positive	1	1
E17 Grid Failure	2	2	1	2	1	1	–	–	–	–	–	–	1
E18 Lack of Supporting Functions	2	2	3	3	1	1	–	–	–	–	–	–	1
E19 Increased Crime	1	2	2	2	1	1	1. Charging station safety incidents. 2. Charger nonfunctional. 3. Charger availability.	–	–	–	–	–	1

Notes: The following notes are for Tables 3.2a and 3.2b.
(a) Data show EV fires are much less common than ICV fires while PHEVs are more problematic. A study also argues that there is insufficient data to draw on (Edmondson 2022).
(b) In California, the Clean Vehicle Rebate Project (CVRP) tracks rebate statistics. In 2021, 13% of total rebates were given to DAC (classified as disadvantaged community based on CalEnviroScreen 3.0). It was 11% in 2020 and 10% in 2019 (slight upward trending). Since 2016, higher-income consumers became ineligible to participate in the CVRP and low-to-moderate-income consumers became eligible for increased rebate amounts.
(c) Annual average energy burden based on average annual housing energy costs divided by the average annual household income.
(d) In 2018, California established a target of 5 million ZEVs by 2030, and 250,000 public EV charging stations, 10,000 of which should be fast chargers. To establish the 2022 target, the team used extrapolation for assuming exponential and linear growth. The estimated 2022 ZEV targets are 1M and 2M, respectively. Then, 1.5 M was used by taking a simple average.
(e) CA AB 1236 and Rule 21: AB 1236 a permitting guidebook was published, and it includes optimal permitting process, current restrictions, and information regarding “permit ready” local jurisdictions. Rule 21 is a comprehensive standard policy for accelerated and streamlined interconnection process for rooftop solar integration.
(f) Reliability of Open Public Electric Vehicle Direct Current Fast Chargers (2022).
(g) (Posky 2022).
(h) By 2040, California projects that nearly 32,000 auto mechanics jobs will be lost. California AB 1966 aimed to create a state fund to help retrain and transition workers from the fossil fuel industry to other non-polluting sectors.
Source: RAND and Sam Schwartz.

CHAPTER 4

Risk Register and Risk Priorities for Connected Autonomous Vehicles (CAVs)

This chapter first presents a synopsis of a review of the literature on agency risks associated with deployment of CAVs. It then presents the risk register for sources of risk associated with CAVs developed from both the literature review and the peer exchanges.

Literature Review on CAV Sources of Risk

State of CAVs

What Are CAVs?

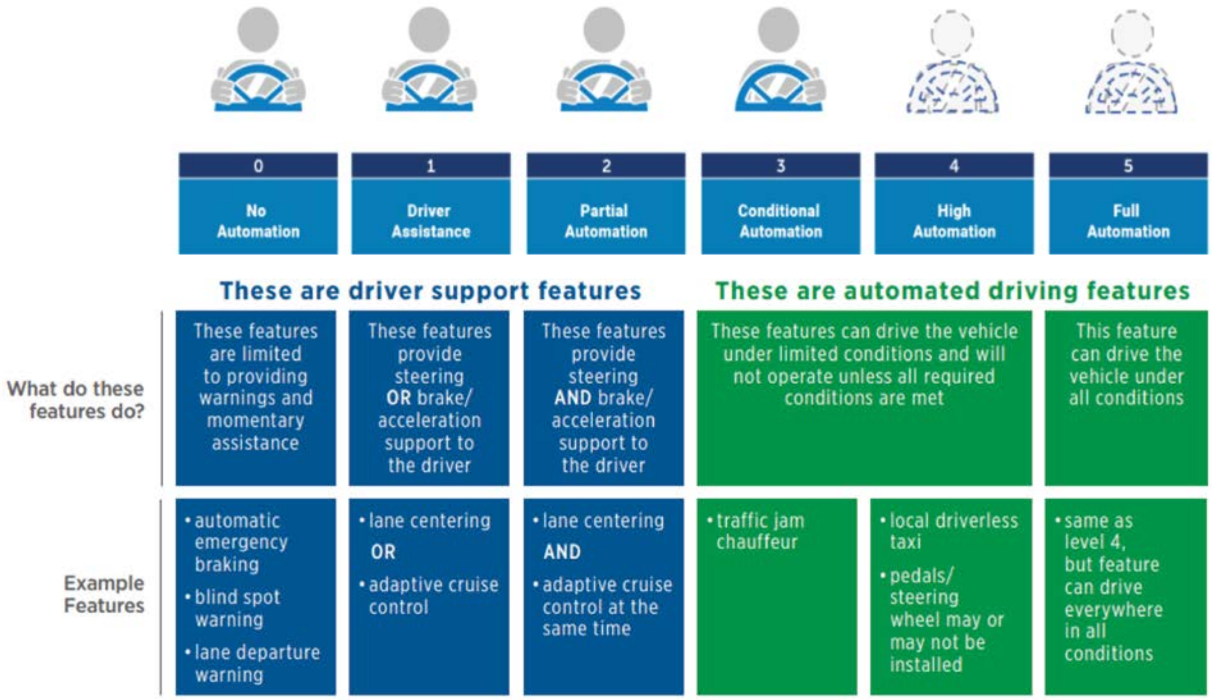
CVs have "applications, services, and technologies that connect a vehicle to its surroundings" (Uhlemann 2015). They enable direct or indirect communication to and between transportation agents using technologies that include but are not limited to DSRC, cellular, Wi-Fi, or satellite (Maddox et al. 2015). Surroundings in the CV context refers to both other vehicles (V2V) and the infrastructure (V2I).

AVs, also referred to as driverless, automated, or self-driving cars are "vehicles that perform all driving functions with or without the human driver" (Pieroni et al. 2018), including "steering, throttle, braking, and motive power selection (forward, reverse, and other), and at various levels of occupant involvement or monitoring" (Maddox et al. 2015).

CAVs possess both connected and autonomous capabilities.

From 2003 to 2007, the U.S. Defense Advanced Research Projects Agency held "grand challenges" that advanced the spread of AV technology (Geng et al. 2017). Autonomous or AV technologies have advanced considerably ever since, with adoption of fully AV ownership envisioned to be between 24% and 87% by 2045 among Americans (Bansal et al. 2017). In another highly cited study, Litman forecasted that AVs will account for around 50% of vehicle fleet, 90% of vehicle sales, and 65% of all vehicles by 2050 (Litman 2022). However, given the challenges in demonstrating the safety and reliability of CAVs before widespread public use, adoption of CAVs may take longer than previous projections have suggested (Kalra and Paddock 2016; Cohen et al. 2019).

For a clear understanding of the current state of CAVs, it is imperative to highlight classification taxonomies for AVs. In September 2016, NHTSA adopted the six-level classification system first proposed by SAE and outlined in the SAE J3016 standard (Zanchin et al. 2017). The standard provides a classification taxonomy ranging from Level 0 (no automation) to Level 5 (full automation) and is currently used by the NHTSA in its Federal Automated Vehicles Policy. The lower two levels of driving automation (Levels 1 and 2) refer to cases in which the human driver continues to perform part of the dynamic driving task (DDT) while the automated system



Source: Six levels of driving automation (adapted from NHTSA and SAE J3016 standard); refer to https://www.sae.org/binaries/content/assets/cm/content/blog/sae-j3016-visual-chart_5.3.21.pdf.

Figure 4.1. SAE definitions for levels of automation.

provides an assistive function (partial automation), such as that used in adaptive cruise control applications or advanced driver assistance systems. The upper three levels of driving automation (Levels 3 through 5) broadly refer to cases in which the automated driving system can scan the environment and perform driving functions with the driver having the option of taking control at any time (NHTSA 2021). Moreover, the NHTSA defines fully autonomous or AVs as "those in which operation of the vehicle occurs without direct driver input to control the steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self-driving mode" (Zanchin et al. 2017).

The most recent SAE standard for CAVs (J3016: Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles) defines the six levels of automation as given in Figure 4.1 (SAE 2021).

It is important to note that the jump from Level 2 to Level 3 (and beyond) is substantial from a technological perspective since the vehicle needs to have environmental detection features using state-of-the-art sensing technologies such as LiDAR (Light Detection and Ranging) as well as capabilities to make informed decisions, such as accelerating past a slow-moving vehicle. Since automated driving technology is still evolving to full maturity, most new vehicles do not neatly fall under the NHTSA/SAE taxonomy and there is ongoing debate among practitioners on the exact characterization of newer vehicles in the market. For example, Tesla's Full Self-Driving Beta release qualifies for classification as a Level 3 or 4 capable technology by the SAE J3016 standard but is self-characterized as Level 2 by the automaker, presumably due to regulatory reasons (Widen and Koopman 2021).

Unconstrained vehicle autonomy (Level 5), using machine-learning and model-based approaches, is too complex a task to fully formalize. Real-time mapping of a dynamic environment, replicating human perception, and higher-level planning decisions for fully automated vehicles remain open challenges for even a restricted operational space (Fridman et al. 2019). The inherent variability in the driving task, the behavior of other human actors, and the constraints faced by existing artificial intelligence (AI)-based systems to come close to human sentience and perception, present the biggest challenge to the deployment of safe and reliable Level 5 CAVs at scale (Kahneman 2011). Moreover, variations in people's moral decisions under various situational factors are biased by their decision-making mode and personal perspective, adding additional constraints. These biases in moral decisions, the so-called AV "trolley problem," highlight the social challenge and add another layer of complexity to the design of a universal moral code for AVs (Frank et al. 2019). The philosophical discourse around sentient AI (and its acceptance in society), precludes one from making predictions about widespread adoption of driverless cars.

However, recent advances in the field of human-centered artificial intelligence—an area of computer science, robotics, and experience design—aim to achieve a deeper integration between humans and AI and would therefore play a critical role in the evolution of technologies with human-AI interaction. MIT's recent Naturalistic Driving Study seeks to collect, synthesize, and analyze data from instrumented vehicles to capture various aspects of human-machine interaction under natural driving conditions (MIT 2021).

Even with ready-to-deploy Level 5 CAVs from a technological perspective, access and affordability of fully automated vehicles may impede widespread adoption. No rigorous economic analysis of fully automated transportation technologies with a focus on dimensions of equity was found in the literature.

Wadud et al. (2016) estimated, based on a survey of self-identified experts, that vehicles would be capable of driving themselves on urban and rural surface roads and highways by 2025 and doing so without a human driver backup by 2030. Optimistic estimates suggested that around 30% of the trucks in the United Kingdom could be automatically driven by 2022 (Wardrop 2009), while up to 75% of the vehicles on the road could be fully automated by 2040 (Jiang et al. 2012). These estimates regarding the timeline and level of adoption of AVs have not materialized. This fact exemplifies the challenges inherent in technology prediction, particularly when dealing with sociotechnical systems that involve complex interactions between technology, regulations, infrastructure, and societal factors. As CAV technology continues to evolve, it is essential to approach predictions and estimations with caution and to embrace modeling and parametric uncertainty when conducting risk assessments.

Private AVs

This modality refers to self-driving vehicles owned or leased by households, often replacing multiple traditional vehicles with one AV. These vehicles are capable of executing a sequence of trips for various household members throughout the day, from differing origin points to diverse destinations, without necessarily requiring round-trip journeys. This includes individual or multiple members from the same household traveling together or separately, provided they are using the same vehicle for their commute.

Automated Carpools

The shared use of a CAV performing a trip is called shared mobility (Shaheen et al. 2015). Carpools or shared rides that include people coming from or going to different destinations constitute a shared drive. For example, a trip that matches people all traveling from the airport to the same neighborhood.

SAVs

SAVs represent an emerging transportation mode with AV fleets (instead of single automated carpools). These may emerge as a potentially transformative approach, supplementing public transportation. Dynamic ridesharing, using CAV fleets, is also referred to as platooning, which provides reduced costs, and time and emission benefits (TRB 2014).

These modalities largely remain conceptual, grounded in current research and technological development (Lempert et al. 2021). Their full implementation is contingent on advancements in CAV technology, evolving regulations, and public acceptance.

Agency Goal: Equity

Depending on the CAV-deployment scheme and market-penetration rates, there are direct and indirect equity implications, including differential effects across populations on physical health (traffic safety, transportation-related physical activity, emissions, exposure to a range of electromagnetic fields), land use patterns, access, and affordability.

In terms of access, most studies contend that travel demand may also grow as automation makes private vehicle travel accessible to groups who do not drive now or drive less than they might like. For example, by mobilizing previously undermobilized populations, CAVs may result in a 14% increase in VMT in the United States (Harper et al. 2016).

CAVs Increase Private Vehicle Ownership

CAVs have the potential to improve accessibility and mobility for people with limited mobility. However, without intentional oversight to ensure equitable benefits, the rise in private CAV usage may unfairly affect historically marginalized populations. Moreover, congestion-related crashes could jeopardize the safety of non-CAV passengers.

Likelihood. Since equity-related hazards are highly dependent on modeling assumptions, they could best be described as having potentially significant but nonquantifiable negative sources of risk.

Signposts. Some early signposts of this risk may include leading indicators such as shifts in demographic patterns, legislative changes suggesting preference for certain modalities, and lagging indicators like CAV ownership trends, Internet/smartphone access, and public transportation usage trends.

Consequences. Most of the sources of risk can be classified as accessibility effects across space (access increases in urban and suburban areas and decreases in external areas) and across social groups (driven by private CAV ownership and market-driven access disparities). On the other hand, shared, platooned CAVs could result in fuel savings of 23% to 39% and reduce congestion by 8% to 13% through mechanisms such as automated intersection management and optimized acceleration and deceleration (Fagnant and Kockelman 2015a). These could have important effects on several agency goals.

Mitigating Actions. For the agency goal of ensuring equitable access to CAVs, the following steps may be taken to reduce inequity risks resulting from private CAV ownership.

DOTs and MPOs can improve equitable deployment of CAVs in their jurisdiction by incentivizing research and deployment of shared CAV fleets and exploring use cases such as low-speed automated vehicles (LSAVs) that are ADA compliant (42 USC §12101) and CAV rollouts that are specifically targeted for older adults. *TCRP Research Report 220: Low-Speed Automated Vehicles (LSAVs) in Public Transportation* provides further deployment guidelines on shared fleets of CAVs with speeds between 15 and 35 mph as an example of equitable CAV use case (Coyner et al. 2021). Similarly, *NCHRP Research Report 896: Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles, Volume 2: Guidance* provides guidelines for local agencies on updating their modeling and forecasting tools to address expected impacts of CAVs on transportation supply, road capacity, and travel demand (Zmud et al. 2018). Research on CAV impact on public revenues shows that ensuing public equity may also require restructuring current tax (property tax, fuel tax) schemes.

Key Gaps in Knowledge. CAV-deployment studies generally look at hypothetical use cases and impacts of CAV rollout modalities are highly sensitive to modeling assumptions and data availability. Data on travel information and travel needs of underserved populations is largely missing and their travel needs and preferences are not adequately modeled, thus resulting in biased projections. Without attention, these populations are likely to be routinely excluded from accessing enhanced mobility through CAVs and related transformational technologies, perpetuating historical disenfranchisement. Research under TCRP Project B-47, "Impact of Transformational Technologies on Underserved Populations" describes the travel metrics and impacts of lack of infrastructure on access to MPOs and DOTs involved in planning CAV deployment in their jurisdictions. The report will be published as *TCRP Research Report 244/ NCHRP Research Report 1101: Transformational Technologies and Mobility Inclusion Playbook.*

CAV Deployment Is Concentrated in Urban Cores

Transformational mobility technologies are predicted to have profound impacts on land use changes, regional economic activity, and transportation demand. CAV deployment may cause denser urban cores, suburban/exurban growth, or a combination of both. By reducing travel costs and improving accessibility (e.g., through concentrating CAV charging infrastructure in urban cores), land values and population densities may increase.

Likelihood. The risk of differential equity impacts across populations is *high* given current trends and may be exacerbated due to continued infrastructure investments and private-sector engagement in urban areas compared to semiurban or rural.

The required heavy initial investment in DSRC roadside units or 5G towers (and connecting fiber) will likely delay deployment of CVs in rural areas unless government subsidies or regulations are employed to spur deployment in semiurban or rural areas.

Signposts. Infrastructure investments and existing pilot programs include but are not limited to EV charging infrastructure (Level 2 and DC fast charging).

Consequences. Most transportation infrastructure investments are location-specific: Investments in downtown cores may increase downtown land values and density while reducing land values and densities in the fringes. Reduced travel costs can improve access and promote the movement of jobs from areas where travel costs are high and technology options are limited (such as rural areas) to urban areas that offer reduced travel costs and better connectivity. This may exacerbate the urban-rural divide, to the detriment of people living in rural areas.

Mitigating Actions. For the agency goal of ensuring equitable access to CAVs, mitigating actions include the following to reduce inequity risks resulting from urban-focused CAV deployment.

Focus on the roadway operating conditions that are unique to rural areas but that have yet to be the focus of CAV and CAV-infrastructure deployment (e.g., wildlife in rural areas may be a concern unless existing training algorithms make use of data that includes unique considerations such as wildlife crossing). Invest in CAV-supportive infrastructure, such as EV charging stations and high-speed broadband/5G, to improve equitable access in rural areas once shared CAV rides reach a cost commensurate with ridehailing services (~$3/mile) (Kittelson & Associates, Inc. et al. 2019).

Key Gaps in Knowledge. There are few rigorous cost-benefit and agency return-on-investment analyses for rural infrastructure development.

Agency Goal: Safety

The NHTSA's estimates for traffic-related fatalities reached 42,915 in 2021, a 10.5% increase from 2020 and the highest number of fatalities from motor vehicle traffic crashes since 2005 (NHTSA 2022). The U.S. DOT's five-pronged approach to reducing serious injuries and deaths includes domains that directly apply to CAV safety such as safer vehicles, safer speeds, and safer roads.

As many states and localities adopt a zero fatalities and serious injuries vision (see Los Angeles County's Vision Zero and the Slow Streets Program), increasingly greater attention is being given to communication, coordination, and collaboration as well as leveraging resources for a safe system approach to traffic safety. The stated goal of the traffic safety culture paradigm "is to develop a process for changing values and attitudes so that safety is part of every transportation decision, whether individual or organizational" (Ward et al. 2018).

CAV Deployment Causes an Increase in Traffic Crashes

Mobility technologies of the future have the potential to increase traffic-related injuries and deaths, especially during early roll out in a mixed vehicle environment. As states role out pilot CAV projects in their jurisdiction, the readiness levels in terms of operational design domain (ODD) elements such as roadway types, geographic area, speed range, environmental conditions, and other domain constraints may vary widely, especially for smaller MPOs and DOTs lacking infrastructure and telecommunications capabilities required for early rollout. For crash reconstruction purposes (including during testing), it is recommended that CAV data be stored, maintained, and available for retrieval, including applicable privacy protections, for crash event data recorders.

Likelihood. The likelihood of such a risk arising may vary by location and safeguards in place and will generally fall in the low-to-moderate range.

Signposts. Signposts for CAV-related safety hazards may include data obtained from a combination of predeployment simulation; test track and on-road testing on metrics, such as crashworthiness, automated system performance during normal and crash avoidance situations; and the performance of fallback strategies during transition to minimal risk conditions. Similarly, a real-time record of post-deployment metrics, such as interventions, injuries, and fatalities due to CAVs, may provide insight into potential safety hazards.

Consequences. Traffic-related crashes attributed to CAV rollout may increase reluctance to CAV adoption and worsen negative public perceptions of CAVs.

Mitigating Actions. For the agency goal of ensuring safety concerning CAVs, mitigating actions may include NHTSA recommendations that entities engaged in CAV testing and deployment publish Voluntary Safety Self-Assessments (VSSAs) to demonstrate to the public and their respective states that they are (1) considering the safety aspects of CAVs; (2) communicating and collaborating with federal agencies such as DOTs; (3) encouraging the self-establishment of industry safety norms for CAVs; and (4) building public trust, acceptance, and confidence through transparent testing and deployment. NHTSA also maintains a list of VSSA disclosures from private companies engaged in CAV testing and deployment. Given that laws and regulations will inevitably change over time, state DOTs may also consider developing processes to update and adapt CAVs to address new or revised legal requirements.

An organizational safety culture ensures reliable operation in safety-critical industries such as the nuclear and aviation industries. The accepted belief system around safety determines the strategies favored by the organization in response to its perceived hazards. A traffic safety agency's response will depend on its capabilities with respect to engineering, enforcement, education, and emergency response services (U.S. DOT 2008). As an example of leadership commitment to safety and safety as a shared organizational goal, the Minnesota Department of Transportation explicitly identified traffic safety culture as a central theme in its Strategic Highway Safety Plan as early as 2014. *NCHRP Web-Only Document 252: A Strategic Approach to Transforming Traffic Safety Culture to Reduce Deaths and Injuries* provides more details on traffic safety culture-based strategies for local MPOs and DOTs to adopt as part of their organizational ethos (Center for Safety Health and Culture and Cambridge Systematics 2018).

Agency Goal: Security and Privacy

Cybersecurity and data privacy are known issues for any sector involving computers and communication networks (Burzio et al. 2018). CAVs are no exception. Recent advancements in CV technologies have led to the creation of new, big, and varied datasets that offer tremendous potential to offer new insights to transportation agencies in managing, operating, and maintaining transportation infrastructure (Pecheux et al. 2020). Big data and its associated lifecycle (creation, storage, usage, and sharing of data) raise privacy and cybersecurity concerns at each step if not managed properly (Mishra and Singh 2016; Pecheux et al. 2020). Moreover, as quantum computing evolves from theory into reality, it introduces a new and potentially dangerous attack vector. Enterprise systems reliant on traditional encryption technologies could become more exposed to adversarial attacks and unauthorized access, intensifying the challenges in ensuring cybersecurity and data privacy (Vermeer et al. 2023). As CAV adoption rates rise, and information sharing among other vehicles, roadway infrastructure, wireless devices, and traffic management systems increases, both CAVs and connected infrastructure are exposed to potentially novel threats. In addition to data or software vulnerabilities, CAVs and the infrastructure system they are connected to are exposed to hardware vulnerabilities as well (Winkelman et al. 2019; Porche 2016). These vulnerabilities and their potential impacts on state and local transportation agencies are discussed in the Cybersecurity Literature Review and Efforts Report from NCHRP Project 03-127, "Cybersecurity of Traffic Management Systems" (Ramon and Zajac 2018). On the federal level, the U.S. DOT has partnered with the automotive industry and industry security experts in programs such as the Crash Avoidance Metrics Partnership and frameworks such as the Security Credential Management System to ensure secure V2V and V2I communication (U.S. DOT 2017).

CAVs Are Successfully Hacked

Security researchers have shown that conventional CVs have already been hacked remotely as early as 2014 (Miller 2019). More connectivity in CAVs will create more entry points for hacking (Burzio et al. 2018), and there is a widespread concern among experts that this risk will only grow (Parkinson et al. 2017). Moreover, evidence from other critical industries (e.g., the power sector) (Narayanan et al. 2020) and the aviation sector (Dave et al. 2022) suggests that if a system is connected to the Internet, it will be a target for hackers, and, at some point, those attacks will be successful.

Likelihood. There is a high likelihood of successful cyberattacks on CAVs for agencies that have inadequate existing safeguards against cyberthreats.

Signposts. Indicators of successful hacking of CAVs could include the following:

Increased Frequency of Cyberespionage Activities. Most cyberthreat-assessment models, such as the cyber kill chain, start with active and passive methods of gathering information on system vulnerabilities (Yadav and Mallari 2016). Moreover, current cyberattacks tend to be more commonly acts of espionage (gaining unauthorized access to a system for information gathering) rather than sabotage (actively compromising a system's normal operation). Such information-gathering activities may portend future acts of sabotage and may also serve as early warning signals for a future, more coordinated attack (Husak et al. 2018), in addition to allowing the attacker to access personally identifiable information (PII) and use it for financial benefit (e.g., to redirect payments from charging or carry out denial-of-service attacks via CAV charging communication channels) (Hodge et al. 2019).

Common Vulnerability Scoring System Metrics. Various publicly listed indicators such as those included in the National Vulnerability Database (maintained by NIST) can provide useful information on future threats to CAVs (Zhang et al. 2015).

Consequences. A key question is what is the impact of a successful attack? The severity of consequences of hacked CAVs will depend on the level of automation of the vehicle (Katrakazas et al. 2020) and sophistication of the cyberattack (Guo et al. 2020). The impacts of such an attack could range from

- Life-threatening consequences of attacks that compromise a platoon of CAVs causing fatal crashes (Khattak et al. 2021).
- Negative impacts on human safety and loss of PII (Hodge et al. 2019).

Successful cyberattacks may also cause significant but nonquantifiable negative impacts on passenger, pedestrian, and worker safety, although the magnitude of such an impact remains uncertain. The FY 2022–2026 Strategic Framework for the U.S. DOT highlights safety as one of its six strategic goals, calling for a ". . . future where transportation-related serious injuries and fatalities are eliminated." The objectives include safe public, workers, and designing systems to improve safety outcomes. The cybersecurity risks associated with CAVs represent a significant concern, not only due to the direct threat they pose to public safety but also because they can endanger the safety of transportation workers. Situations in which CAVs are compromised through hacking can create hazardous conditions that may potentially cause injury or even fatal harm to maintenance crews.

Mitigating Actions. State DOTs and MPOs in consultation with federal agencies such as Cybersecurity and Infrastructure Security Agency (CISA) can jointly work to develop and implement employee training and exercises to ensure agency personnel are aware of cyberphysical risks and potential infrastructure vulnerabilities. Over time, there has been an evolution in the preferred methods of training delivery for DOT employees, although there is still a strong preference for print/electronic materials. Conferences, peer exchanges, and web-based seminars on cyber-related threats may increase awareness, and thereby reduce the risk of interconnected cyberphysical threats. Similarly, participation in cybersecurity awareness activities such as those provided by CISA can help identify potential vulnerabilities before they manifest as serious threats.

Cyberthreats are twofold: attacks on CAVs and attacks on CAV-connected infrastructure. DOTs can minimize risk to infrastructure by protecting the boundary between CAVs and transportation infrastructure. The term "boundary" here refers to the points of communication or interaction (both physical or digital) between CAVs and the broader transportation infrastructure. Digital systems may include communications over Wi-Fi, 4G/5G networks, or DSRC systems, and physical systems may include roadside units (RSUs), traffic lights, or smart road signs.

Cyber risk can be minimized by establishing separate, secure communications networks for the most critical cyber networks, including backup communications during emergencies (Cybersecurity and Infrastructure Security Agency 2017). Updating current maintenance practices by incorporating connected infrastructure elements such as asset management lists for RSUs can reduce cyberthreats. Given the nonuniform distribution of current CV deployment across the United States, state DOTs and MPOs can also benefit from sharing best practices and lessons learned to continuously improve transportation asset management practices (U.S. DOT 2021).

Key Gaps in Knowledge. Although there is near certainty regarding successful CAV hacking due to potential hardware and software vulnerabilities, the full implication for human safety is uncertain. Similarly, infrastructure security faces a moderate-to-high risk from successful CAV hacking, depending on the vehicle's level of automation and deployment mode, among other factors.

CAV-Connected Infrastructure Is Successfully Hacked

Cyberattacks may exploit vulnerabilities in the entire cyberphysical system, including vehicle operation, the communications system, the connected infrastructure, and in-vehicle sensors (Cybersecurity and Infrastructure Security Agency 2021; Sheehan et al. 2019). However, future attacks on CAVs are expected to target vulnerabilities in the connected infrastructure, rather than the simpler elements of the vehicles (Kim et al. 2021). Concerns about software hacking and safety implications of AVs are among some of the top-reported concerns globally (Kyriakidis et al. 2015).

Since today's infrastructure systems combine both cyber and physical components, cyber risks are increasing and include the risk of a cyber incident not only compromising data but also the control systems of critical infrastructure operated by transportation agencies, such as tunnel ventilation systems (Presidential Proclamation 2021; Countermeasures Assessment & Security Experts, LLC and Western Management and Consulting, LLC 2020).

Likelihood. Similar to successful hacking of a CAV, there is a high likelihood of successful cyberattacks on infrastructure connected with CAVs.

Signposts. Early warning signs such as passive information gathering may portend cyberthreats to CAV-connected infrastructure. Attack vectors or pathways a malicious actor takes to access CAV-connected infrastructure could range from physically altering road signs an AV relies on to navigate (e.g., using paint or reflective stickers to alter stop signs) to more sophisticated, remote attacks on CAV operation and communication systems (Cybersecurity and Infrastructure Security Agency 2020).

Consequences. CAV functionality depends on perception algorithms to accurately detect and respond to infrastructure based on sensor information. A hacked roadway message could cause collisions involving people or property or a temporary disruption of traffic signs (Kelarestaghi et al. 2018). A more sophisticated attack compromising CAV operation and communication systems could lead to enterprise-level consequences, including cascading supply chain disruptions and financial losses (Cybersecurity and Infrastructure Security Agency 2020).

Successful cyberhacks pose a moderate-to-high negative impact to transportation agency goals around critical and noncritical infrastructure security.

Mitigating Actions. In addition to the mitigating actions mentioned in the CAVs Are Successfully Hacked section, the following actions may reduce the likelihood of hacked CAV-connected infrastructure. CAV infrastructure refers primarily to DSRC equipment but can also refer to supporting infrastructure needed for deployment such as backhaul communications, data analytics, and related operational domain elements. CAV-connected infrastructure will, in theory, have wide-ranging benefits, including but not limited to targeting externalities such as congestion. Additionally, state DOTs may consider investing in areas such as advanced traffic management systems, digital twin technologies for simulating and optimizing CAV operation, roadside sensor technology, and more visible road markings, in addition to capacity building and skill development of their workforce in these domains.

Key Gaps in Knowledge. Key gaps include funding availability and the fact that reliable information on maintenance costs and return on infrastructure investments is not readily available. Different jurisdictions will have varying levels of interest in deploying CAVs and associated infrastructure (based on perceived benefits), and limited availability of the CAV infrastructure will seriously impede the ability of AVs to operate everywhere and is likely to deter growth of the overall market for CAVs.

Big Data from CAVs Raises Ownership and Privacy Concerns

In the context of CAVs, big data—frequently referred to as the Internet of vehicles data—can be data from vehicles, passengers, roadside infrastructure, and the Internet (Xu et al. 2018). Public-private partnerships to standardize, share, and protect sensitive data can be key to leverage benefits of CAVs to MPOs and DOTs and encourage innovation. CAV manufacturers, service providers, and transportation departments track several important datapoints across the data lifecycle; starting with creation (observing, gathering, or creating new data), storage (writing collected data to secured, cloud-based storage platforms), usage (performing analysis), and sharing (disseminating data to appropriate internal and external recipients) (Data Management Association International 2017). Concerns regarding ownership and privacy of collected data (as well as liability of state MPOs and DOTs) may arise across any of these lifecycle phases and require tailored approaches to ensure there is no breach of consumer privacy. The vast and varied nature of data collected from a CAV's onboard system and as a result of its interaction with connected infrastructure has potential applications not just for optimizing vehicle performance and safety features but also for city planners, traffic managers, insurance industries, and other parties. There can be issues regarding who possesses rights to this data and who can profit from it. Questions on data ownership, interoperability, exchange, and quality are important and may include

- Who should own or control the vehicle's data?
- What types of data will be stored?
- With whom will these datasets be shared?
- In what ways will such data be made available?
- For what ends will the data be used?

Likelihood. There is a moderate-to-high likelihood of breaches of consumer privacy, given that appropriate data management frameworks are applied by MPOs and DOTs across the CAV data management lifecycle.

Signposts. Watchful oversight of infrastructure and communication technologies—including monitoring of hardware and software vulnerabilities—can help detect early warning signs of a data breach. Malware injection through software patches, such as the widespread 2020 Orion software patch that affected a wide range of federal departments and private businesses, are Trojan horse attacks where hackers exploit vulnerabilities across a software supply chain to gain unauthorized access. Signposts that could suggest potential data breaches or misuse in the realm of CAVs might include unusual network traffic patterns or anomalies in data access logs, which may indicate unauthorized attempts to access or manipulate data.

Consequences. Illegal data access can breach user privacy (such as travel behaviors, routes, and personal information) and aggregated user data can also be used in nefarious ways (such as microtargeted advertising, or socioeconomic profiling). On the other hand, responsible use can help traffic managers devise better congestion pricing schemes and reduce congestion and CAV-related GHG emissions.

Mitigating Actions. User privacy and security should be a prerequisite for trustworthy and reliable deployment of CAVs. Continuous evaluation of data storage, access, and transfer processes using performance evaluation metrics can mitigate potential threats.

Because data ownership and user privacy are concerns likely to evolve and potentially become more serious as more user information (on drivers, owners, renters, passengers) is stored, accessed, and moved over multiple channels, measures for risk assessment governing user data should evolve in tandem. While most cybersecurity protections look for bold and brash attacks, most successful cyberattacks have been subtle and relatively well hidden (Eliot 2021). Data interoperability standards, cloud storage of user information, and protocols for data access should be continually updated in line with the latest industry practices.

A strict data QA regime, particularly for software-related vulnerabilities from third-party vendors where there is an opportunity that something malicious may be inserted, can highlight threats before they evolve into systemwide cybersecurity incidents. This might mean strengthening existing IT infrastructure security and risk assessment processes or introducing more robust data handling practices at a state, local, and federal level, along the lines of international benchmarks such as the European Union's (EU's) General Data Protection Regulation (GDPR) and its associated ePrivacy directive (2016/679).

Key Gaps in Knowledge. Existing federal privacy legislation, such as the Drivers' Privacy Protection Act (1993) and the Electronic Communications Privacy Act (1986), are largely inapplicable to CAVs/AVs due to the emerging nature of autonomous technologies, potential implementation modalities, and lack of explicit guidance on the myriad ways that CAVS may collect, transmit, and store data. Moreover, peer-reviewed literature on best practices for CAV cyber readiness is scant.

Agency Goal: Sustainability and Environment

CAV Deployment Increases Congestion

Transport-related emissions represent about 30% of all GHG emissions (U.S. EPA 2021). Transformational mobility technologies are predicted to have profound impacts on regional economic activity and transportation demand. CAVs are no exception; their deployment may cause denser urban cores, resulting in additional congestion due to larger-than-baseline VMT. Increased VMT may have the risk of externalities such as an increase in incremental transportation-related emissions exposure and resulting adverse health impacts.

This hazard can result in the risk of exacerbating exiting inequities from pollution exposure.

Likelihood. The likelihood of CAV deployment increasing non-CAV and overall GHG and PM emissions, and therefore exposure, is moderate-to-high.

Signposts. CAV impact on congestion can be tracked by monitoring and comparing time series data on VMT and travel times between free flow and congestion. PM pollution data on a hyperlocal level may indicate differential pollution impact from CAV deployment. Moreover, source emissions from CAVcharging and lifecycle emissions from CAVs can be approximated ex ante by emissions inventories from EVs.

Consequences. The impacts from light-duty CAVs could include more VMT resulting in congestion adding to travel times and increased emissions.

Mitigating Actions. To ensure that sustainability and climate change goals are not disadvantaged by CAV-deployment, agencies can prioritize multimodal transit networks that reduce overall VMT and may provide the added benefit of reduced congestion.

A simulation study for the Chicago Transit Authority and Metra (commuter rail) in the Greater Chicago Metropolitan area showed how reallocation of resources between shared autonomous vehicle fleets and conventional public transit may improve the travel experiences of current transit users, in terms of average wait times, relative to the existing transit system, without incurring additional cost to transit agencies (Pinto 2020).

Key Gaps in Knowledge. Simulation-based results may vary from real-life situations. This is a recurring gap due to existing metrics being based on simulations with inherent model or parametric uncertainties.

Agency Goal: Internal—Budget

CAV deployment requires various ODD elements to be in place before public rollout. Moreover, other than capital costs for infrastructure retrofits, redistribution, introduction of new elements and changes in roadway geometric design, operations and maintenance costs for CAV infrastructure are highly uncertain. Safe operation of CAVs depends on perception algorithms to accurately detect and respond to infrastructure based on sensor feedback. Uncommon conditions such as wildlife crossing in rural areas may be more challenging and may require additional infrastructure for safe operation.

This hazard can result in transportation agencies running the risk of cost and time overruns for capital projects.

Likelihood. The likelihood of CAV-related cost and time overrun risks is moderate-to-high and may arise due to technical, economic, and political issues defined in the risk register.

Signposts. These are indices, such as the Automated Vehicles Readiness Index which is a weighted average of policy, physical, and cyber-readiness metrics, to rank-order cities by their readiness levels for CAV operation. Infrastructure readiness level can inform better estimates for cost requirements (KPMG 2020).

Consequences. If the added costs are passed on to consumers, CAV cost per mile may be adversely affected due to cost overruns and may drive down user acceptance of CAVs.

Mitigating Actions. MPO and DOT budgets and current design standards and guidelines for infrastructure should include provisions for future V2I and I2V investments in addition to known investments in CAV-friendly roadway markings, visible or retroreflective signage, and barriers between other road users and CAVs. In addition to hardware, the communications technologies (in particular, DSRC) for CVs operate in licensed radio frequency spectrum and the uses allowed for unlicensed spectrum are important considerations for MPOs and DOTs since allowing more devices in the licensed spectrum may cause interference (in crowded jurisdictions) and safety-related issues. This may result in disproportionate deployment opportunities across states.

Key Gaps in Knowledge. Since CAV technology and associated infrastructure requirements are evolving rapidly, no readiness index currently exists to evaluate a priori cost estimates, especially as they relate to infrastructure operations and maintenance.

Agency Goal: Internal—Tort Liability

Agencies need to include potential exposure to tort liability among their internal risk management concerns.

State-Specific CAV Regulations Pose Liability and Preemption Concerns

In the case of a CAV crash, inconsistent state or agency law may lead to liability or preemption when a federal statute explicitly or implicitly preempts state law. As an example, product manufacturers may argue that federal regulations preempt inconsistent state tort law and preclude lawsuits by injured plaintiffs. Tort law addresses civil wrongs (i.e., torts) that cause injury or harm. A common tort in product liability is negligence, which may expose state DOTs to issues involving CAV infrastructure.

This hazard can result in transportation agencies running the risk of facing lawsuits under tort law.

Likelihood. The likelihood of CAV-related product liability laws affecting transit agencies is *low*.

Signposts. Monitoring number, scale, and nature of tort liability cases (specifically for Level 3 or 4 vehicles) for claims, precedents, and legal outcomes.

Consequences. Consequences include possible liability claims, such as those arising from negligence, misrepresentation, design defect, and failure to warn.

Mitigating Actions. State-level legislative clarity regarding AV liability can be beneficial. Researchers contend that congressional preemption of state tort remedies for AV liability should not be considered in the absence of a comprehensive federal regulatory regime. State courts should continue to apply state tort remedies (Villasenor 2014).

CAV Risk Register by Risk Priority

The risk register of potential sources of risk from CAVs is presented in a pair of tables: Tables 4.1a and 4.1b. Table 4.1a provides information typically found in a standard risk register (while applying the exceptions discussed in Chapter 2). This table presents its rows in descending order of assessed risk priority. Table 4.1b provides data that underly the calculation of both forms of the LOC measure, the SI-LOC and CB-LOC measures (see Chapter 2). These data are useful for raising awareness within the agency of the relevant aspects of a source of risk from emerging and disruptive technologies to agency goals. Therefore, each pair of tables provides more detail than is typical of standard risk registers to present the underlying methodology so that agencies can make modifications that will support their own deliberations and risk prioritization. The full methodology for doing so is found in Appendix C.

The same data appearing in Tables 3.1a, 4.1a, 5.1a, and 6.1a are presented in Appendix B sorted by agency goal.

Tables 4.1a and 4.1b are followed by a review of the literature on potential hazards (sources of risk) connected with CAVs.

Table 4.1a. Risk register by risk source (hazard) for CAV technology group.

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
C1 Hacked Infrastructure	CAV-connected infrastructure is successfully hacked.	Projected vulnerabilities of infrastructure/ industrial control systems.	4	Security and Privacy	1. Targeted congestion during on-ramp merging on highways (Zhao et al. 2021). 2. Life-threatening consequences of attacks that compromise a platoon of CAVs causing fatal crashes (Khattak et al. 2021). 3. Negative impacts on human safety and loss of PII (Hodge et al. 2019).	**4**	Invest in CAV infrastructure: upgrade cybersecurity protocols and conduct regular security audits and stress tests.	State DOTs and MPOs with potential matching federal funds.	**Extreme**
C2 Hacked Vehicle	CAVs are successfully hacked.	Projected vulnerabilities of CAV technologies (e.g., vehicle sensors, Internet-connected/ edge devices).	4	Security and Privacy	Allows the attacker to access PII and use it for financial benefit (e.g., to redirect payments from charging or carry out denial-of-service attacks via CAV charging communication channels) (Hodge et al. 2019).	**3**	1. Increasing cybersecurity awareness. 2. Implementing strong authentication protocols, monitoring network traffic for suspicious activities, and ensuring secure communication channels between CAVs (private) and infrastructure (public) components.	Federal/ state/local DOTs, MPOs.	**Extreme**
C3 Agency Workforce Obsolescence	CAV deployment increases the skills gap across the workforce.	Agency-specific skills gap analysis.	3	Workforce	This hazard can result in higher rates of retirement, higher obsolescence of skills in the existing workforce, and unforeseen budget requirements for agencies.	**3**	Target foreseeable human resource requirements for data-centric jobs (data science, curation, analytics, and business intelligence) and improve attractiveness through revised compensation, particularly for contract/ temporary workforce.	State DOTs, MPOs.	**High**

C4 Increased Congestion	CAV deployment increases congestion.	Pre- and post-deployment metrics (such as VMT, vehicle occupancy rates, GHG emissions) from scientific literature.	2	Sustainability	The impacts from light-duty CAVs range from overall and CAV-related VMT, energy usage, and GHG and criteria pollutant emissions may vary widely depending on factors such as travel demand patterns, CAV-deployment modalities, and CAV technologies used.	**4**	1. Prioritize multimodal transit networks: integrating shared autonomous fleets with existing transit systems reduces total travel time and incentivizes the use of public transit. 2. Encourage shared autonomous fleets for more equitable access to CAVs for low-income or previously under-mobilized populations.	State DOTs, MPOs, and local, tribal, territorial, agencies.	**Moderate-High**
C5 Liability and Preemption Concerns	State-specific CAV regulations pose liability and preemption concerns.	Past tort liability cases (specifically for Level 3/4 vehicles) for claims, precedents, and legal outcomes.	4	Internal—Tort Liability	Liability claims such as those arising from negligence, misrepresentation, design defect, failure to warn, etc.	**2**	Seek legislative clarity on state tort laws. Generally, researchers contend that states can take the lead in regulating testing, and administrative procedures, such as licensing, without much risk of preemption. However, NHTSA is highly likely to preempt in case of safety violations.	State DOTs, MPOs, and local, tribal, territorial agencies in consultation with DOT (FMCSA/ NHTSA).	**Moderate-High**
C6 Increased Car Ownership	CAVs increase private vehicle ownership.	Projected CAV rollout modality and trends in car ownership.	2	Equity	Increased CAV deployment may reduce accessibility and create disparities due to private ownership and market-driven access. Literature suggests decreased private ownership in the long term, but high-end personal CAVs could emerge in 3 to 4 years.	**3**	1. Incentivizing shared CAV fleet deployment. 2. Tracking progress on transportation equity.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**
C7 Reduced Affordable Transportation Options	Reduction in affordable transportation options due to high up-front costs of CAV-ready infrastructure.	Trends in private CAV infrastructure (e.g., V2I technology, charging stations) investment vs. improvement in transit operations.	2	Equity	May exacerbate existing affordability/ access considerations resulting in distribution equity challenges.	**3**	1. Investing in multimodal transit networks by integrating shared autonomous fleets with existing transit systems. 2. Ensure appropriate subsidies/incentivization of shared autonomous fleets over private vehicle ownership.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**

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Table 4.1a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	**Signpost Indicators to Watch**	**Likelihood Proxy**	**Goal Affected**	**Potential Consequences**	**Severity Score**	**Potential Mitigating Actions**	**Action Owners**	
C8 Urban Deployment	CAV deployment is concentrated in urban cores.	Charging station density per 100,000 persons or square mile.	3	Equity	Investments in downtown cores may increase downtown land values and density while reducing land values and densities in the fringes. Might make urban living more desirable, increasing housing/parking/ congestion costs.	**2**	1. Investing in CAV-ready infrastructure such as EV charging stations and high-speed broadband/5G, may improve equitable access in rural areas. 2. Agency readiness self-assessment.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**
C9 Increased Crashes	CAV deployment causes an increase in traffic-related crashes.	Crash statistics from pilot CAV deployment.	2	Safety	Traffic-related crashes attributed to CAV rollout may increase reluctance to adopt CAVs and worsen negative public perceptions about CAVs.	**3of**	1. VSSAs to promote safety norms and public acceptance. 2. Integrating and incentivizing traffic safety culture in industry planning processes and practices.	State DOTs, MPOs, and local, tribal, territorial agencies, in consultation with NHTSA and private partners.	**Moderate-High**
C10 High Up-Front Cost Needed	CAVs require unforeseen investments in physical and digital infrastructure.	Net present value/financial analysis based on CAV-deployment costs (labor, infrastructure, etc.).	2	Internal—Budget	This hazard can result in transportation agencies running the risk of cost and time overruns for capital projects.	**3**	Budget provisions and updated design guidelines: MPO/DOT budgets and current design Standards and Guidelines for infrastructure should include provisions for future V2I and I2V investments in addition to known investments in CAV-friendly roadway markings, visible or retroreflective signage and barriers between other road users and CAVs.	State DOTs, MPOs, and local, tribal, territorial agencies in consultation with third-party contractors (e.g., cyber-security consultants, and civil engineering services firms).	**Moderate-High**

C11 Inequitable Opportunities	CAV deployment increases the opportunities gap across demographics.	Agency-specific opportunity gap analysis.	3	Equity	This hazard can result in perpetuating existing structural inequities across the transportation agency workforce.	**2**	Update recruiting, training, retraining, and succession management practices to attract a wider pool of talent.	State DOTs, MPOs.	**Moderate-High**
C12 Air Pollution and GHG Emissions	CAV adoption hinders agency goals for GHG/air pollution (PM2.5, nitrogen oxides/sulfur oxides) emissions reduction.	Correlation of ambient pollution with traffic volume.	2	Sustainability	1. Failure to meet agency goals regarding sustainability and climate change. 2. Reduced federal. and state funding	**2**	1. Clarify CAV testing, deployment, and operation guidelines for private-sector stakeholders. 2. Require prospective studies on CAV-related emissions costs/benefits for testing/operation.	State DOTs, MPOs.	**Moderate**
C13 Data Privacy	Big data from CAVs raises ownership and privacy concerns.	Benchmarking against global standards for privacy/cybersecurity.	2	Security and Privacy	Illegal data access can breach user privacy (such as travel behaviors, routes, personal information, etc.) and aggregated user data can also be used in nefarious ways for political purposes (such as identifying voting preferences, targeted advertising, etc.).	**2**	1. Robust risk assessment measures. 2. QA checks on data workflows by third-party auditors.	State DOTs, MPOs.	**Moderate**

Source: RAND and Sam Schwartz.

Table 4.1b. Elements of two likelihood proxies and overall results for the CAV technology group.

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Infor-mation	Response		Metric	Target	Tolerance Level (+/-)				
C1 Hacked Infrastructure	3	3	3	4	4	4	Information on potential zero-day vulnerabilities (e.g., via public-private data interoperability standards) that may portend cyberthreats to CAV-connected infrastructure.	—	—	—	—	—	4
C2 Hacked Vehicle	2	3[a]	2	2	3	4	1. Increased frequency of cyberespionage activities. 2. Common vulnerability scoring system metrics.	—	—	—	—	—	4
C3 Agency Workforce Obsolescence	2	2	1	2	3	3	1. Existing gaps in computer-related skills such as data science or analytics, or the need for retraining of existing staff. 2. Identify gaps in core competencies across agency in a systematic way and compare against peers in regional agencies.	—	—	—	—	—	3
C4 Increased Congestion	2[b]	2	3	2	2	2	1. Predeployment metrics from published studies/simulations/surveys from literature. 2. Post-deployment metrics: time series data on VMT, occupancy rates, and average trip duration.	—	—	—	—	—	2
C5 Liability and Preemption Concerns	2	3[c]	1	3	3	4	Consumer perceptions and safety statistics of CAVs.	—	—	—	—	—	4

C6 Increased Car Ownership	2[d]	3[e]	2	1	2	2	1. Projected CAV rollout modality (% shared AVs). 2. Projected impact on car ownership (% decrease).	1. Shared AV Fleet (% of total cars) = 1% to 2% by 2030s. 2. Private CAVs projected to be 5% of total vehicle sales by 2030.	Uncertain	On Target	Negative	2	2
C7 Reduced Affordable Transportation Options	2	2	3	2	2	2	Indices such as the Autonomous Vehicles Readiness Index and existing budget apportionment for private vs. transit-oriented/shared CAV deployment.	—	—	—	—	—	2
C8 Urban Deployment	1	2	3	1	2	1	1. 1.2M chargers required for public use by 2030. 2. Infrastructure investments and existing pilot programs, including but not limited to EV charging infrastructure (Level 2 and DCFC).	1. At ~150k public-use chargers at ~50k charging stations nationwide today, we need ~150k new EV chargers/year to meet targets for electrification under federal ZEV sales target. 2. Public EV charging stations per 100,000 households: ratio of high-income urban districts to low-to-moderate urban districts.	Conserv-ative target (tolerance ~5%)	Out of Tolerance	Negative	3	3

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Table 4.1b. (Continued).

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Infor-mation	Response		Metric	Target	Tolerance Level (+/-)				
C9 Increased Crashes	3	2	3	1	2	2	1. Predeployment metrics such as test track and on-road testing on metrics such as crashworthiness, and automated system performance during normal and crash avoidance situations. 2. Post-deployment metrics such as interventions, injuries, and fatalities due to CAVs may provide insight into potential safety hazards.	—	—	—	—	—	2
C10 High Up-Front Cost Needed	3	2	1	3	2	2	Indices such as the Autonomous Vehicles Readiness Index which is a weighted average of policy, physical, and cyber-readiness metrics to rank-order cities by their readiness levels for CAV operation.	—	—	—	—	—	2
C11 Inequitable Opportunities	2	2	1	2	3	3	1. Identify existing workforce composition and gaps in diversity metrics. 2. Prioritize diversity, equity, and inclusion in hiring practices, if absent.	—	—	—	—	—	3

C12 Air Pollution and GHG Emissions	1	2	4	1	2	2	1. Follow EV Level 3 or 4 vehicle trends (monthly/annual sales) as a precursor to CAV adoption. 2. Monitor CAV-associated infrastructure readiness (e.g., charging station geolocation and access data).	—	—	—	—	—	2
C13 Data Privacy	2	2	4	2	2	2	1. Agency compliance with global data privacy standards such as the EU GDPR. 2. Information on privacy concerns from data breaches across federal/state government systems (e.g., 2020 Orion software patch attack).	—	—	—	—	—	2

Notes:
(a) Considering private CAV as the dominant mode.
(b) Would depend on deployment-modality. However, the assumption that shared CAVs can contribute to congestion reduction, GHG mitigation, and equity goals is well-supported in existing literature.
(c) Agencies should be more concerned about velocity here since early, wealthy adopters and liability claims are crucial.
(d) Hazard-tech is not novel, but Level 4/5 may contain novel elements.
(e) Adoption rate is high for private CAV rollouts for early high-end adopters. Tesla's Full Self-Driving uptake was 46% at \$2 to \$3K but 7% worldwide at ~\$12K now (2022).

Source: RAND and Sam Schwartz.

CHAPTER 5

Risk Register and Risk Priorities for Mobility on Demand/Mobility as a Service (MOD/MaaS)

This chapter presents the risk register that resulted from applying the method outlined in Appendix C to the input received from a literature review and the results from peer exchanges. We first present a synopsis of a review of the literature on agency risks associated with deployment of MOD/MaaS. The risk register necessarily requires concise language for presentation. By first presenting several of the literature review findings, the report will help readers gain fuller benefit from the risk register that then follows.

Literature Review on MOD/MaaS Sources of Risk

What Is MOD/MaaS?

MOD. As defined by SAE International, MOD is the "concept envisioning an interconnected and coordinated mobility ecosystem to meet the needs of all users by providing the safe, reliable, and efficient movement of travelers and goods. MOD offers users personalized mobility and goods delivery options on request, matched with coordinated network strategies of service providers and operations managers" (SAE 2021). MOD takes a user-focused approach to ensure that new emerging modes are "developed alongside existing services in an integrated fashion to foster a fluid and connected transport system incorporating all modes and people in a seamless fashion" (U.S. DOT 2023).

MaaS. MaaS is a "concept envisioning integrated mobility where travelers can access multiple transportation modes over a single digital interface (see Figure 5.1). MaaS primarily focuses on passenger mobility allowing travelers to seamlessly plan, book, or pay for travel on a pay-as-you-go or subscription basis" (SAE 2021). While MOD focuses on the user, MaaS focuses on the technological aspects, enabling users to plan, book, and pay for multiple transportation modes using a single interface (AASHTO 2023).

MOD and MaaS act as basic essential elements to enable shared multimodal mobility into regional transportation systems. MOD and MaaS facilitate shared mobility services such as car rentals, paratransit, pedicabs, taxis, carpools, bikeshares, carshares, courier network services, microtransit, transportation network companies (TNCs), and scooter share among other core and innovative transportation services (Shaheen et al. 2017). MOD and MaaS thus pose similar challenges to agency goals, which can be categorized as risks to (1) overall mobility, (2) safety, (3) privacy and security, (4) equity and inclusion, (5) public health, (6) public acceptance, and (7) the workforce. It is also important to note that some risks and challenges described in the risk register and the literature review are associated with shared modes and modes of transportation that are available through MOD/MaaS and not necessarily MOD/MaaS platform risks.

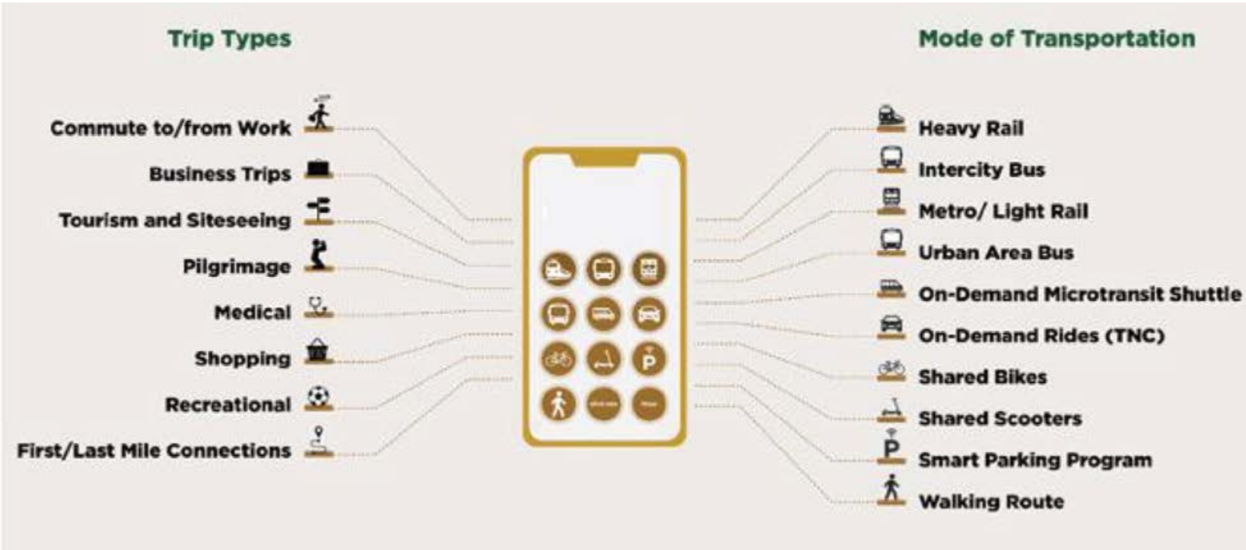


Figure 5.1. Idealized illustration of a MaaS phone app.

Cities across the world are piloting partnerships with MaaS providers to test the potential of service-based transportation. Helsinki is often cited as a leader in the field. Since 2016, residents and visitors of Finland's capital can use the app Whim to access taxis, carsharing, bikesharing, and public transit. Users can choose a monthly all-inclusive subscription or pay as they go. Ubigo in Gothenburg, Sweden; Ustra in Hannover, Germany; Moovel in Berlin, Germany; Mobility in the Netherlands; and Move PGH in Pittsburgh, Pennsylvania, are representative examples of MaaS deployments at various stages.

Agency Goal: Mobility

Mobility is the ability to move freely and easily within a defined geography, such as cities, metro areas, and regions. MOD and MaaS present a risk to mobility since they facilitate the proliferation of vehicles on our streets. The growth of TNCs, coupled with an exponential surge in e-commerce deliveries in recent years, has increased VMT, pickup/drop-off, curb-space competition, and overall congestion (which also have environmental implications), especially in urban areas. MOD/MaaS can disrupt mobility in two ways: via (1) increased traffic congestion and (2) right-of-way conflicts.

Increased Traffic Congestion

While the availability of high-capacity transit, microtransit (IT-enabled multipassenger transportation), and other space-efficient modes such as micromobility (e.g., e-scooters, e-bikes, bikes) effectively reduce congestion in urban areas, TNCs and taxis can add to urban congestion when they replace such modes or induce ridership. Schaller (2018) identified valid concerns about the increased congestion from TNCs in cities in the 2010s:

- TNCs added 5.7 billion miles of driving in the nation's nine largest metro areas while car ownership grew more rapidly than the population.
- About 60% of TNC users in large, dense cities would have taken public transportation, walked, biked, or not made the trip if TNCs had not been available for the trip, while 40% would have used their own car or a taxi.

Right-of-Way Conflicts

MOD/MaaS is one of many activities with competing demands for limited street and curb space (Shaheen et al. 2017a). The surge in MOD/MaaS trips can lead to modal conflicts (e.g., between cyclists and vehicles at the curb), add to congestion in high-traffic areas, or block access for pedestrians or people with disabilities (e.g., vehicles blocking curbs, ramps, or loading zones) (Shaheen et al. 2020). When unregulated, MOD/MaaS may also prove adverse to the public right-of-way.

Besides potentially obstructing movement, dockless bikes and scooters left on sidewalks or users riding on sidewalks may make pedestrians and people with disabilities feel unsafe or uncomfortable (Shaheen and Cohen 2019). For example, during the 2018 Portland scooter-sharing pilot, over a quarter of the public comments the Portland Bureau of Transportation (PBOT) received were complaints about illegal sidewalk riding (Shaheen and Cohen 2019).

Agency Goal: Safety

MOD/MaaS is often used to access micromobility devices (bikes, scooters, and other low-speed modes), which pose physical safety risks to users, mostly due to their relatively greater vulnerability in traffic crashes with vehicles. Additionally, consumers may be at risk in cases where MOD/MaaS are being used to access rideshare services where a customer must interface with a driver. Without proper oversight to vet out dangerous individuals from becoming drivers, or regulation to keep drivers from staying behind the wheel for dangerous amounts of time without proper rest, consumers may be putting themselves in danger when they enter a TNC vehicle. Thus, risks to safety from MOD/MaaS include (1) road crashes and (2) TNC safety risks.

Road Crashes

Micromobility users (and pedestrians) are the more vulnerable parties in crashes with vehicles, which are larger, faster, and heavier. Similarly, pedestrians are generally more vulnerable when involved in crashes with micromobility users. In locations where pedestrian amenities (such as crosswalks and sidewalks) or micromobility facilities (such as dedicated lanes or multiuse paths) are lacking, sharing space with vehicles on the road or pedestrians on the sidewalk can create conflicts and safety challenges.

Although studies on the safety of micromobility are limited, one study on Los Angeles' scooter share suggests that scooter-related injuries are common and there are low rates of adherence to rider age requirements and low rates of helmet use (Shaheen and Cohen 2019). A different study that focused on Portland's 4-month scooter-sharing pilot in 2018 found that 83% of scooter-related emergency visits did not involve another mode, 13.6% involved a vehicle, 2.8% involved a pedestrian, and one emergency visit (0.6%) involved two scooters. Intoxication was reported in 16% of emergency visits. The emergency room reports contained insufficient data on helmet use in the collisions, but PBOT estimated that 90% of riders did not wear helmets (Shaheen and Cohen 2019). Helmet usage tends to be lower among shared micromobility users, but this does not necessarily mean that these modes are more dangerous; more research is needed to understand what contributes to user injuries (Shaheen et al. 2020).

Annual crash rates are relatively low among North American station-based bikesharing operators: A study in 2013 found an average of 4.33 crashes per year among operators with more than 1,000 bicycles (Shaheen and Cohen 2019). Bicycle collisions generally rise in cities with these bikeshare systems, but this increase is likely due to a growth in bicycle activity overall (Shaheen and Cohen 2019). In addition, bikeshare bicycles may be safer than some personal bicycles because they are generally brightly colored, have heavier frames, and have fewer gears, making the ride generally slower and increasing the ability to react to unexpected situations on the road (Shaheen and Cohen 2019).

Agency Goal: Privacy and Security

Critical to MOD/MaaS are the digital platforms that allow access and facilitate shared mobility services. Thus, collecting and sharing data is integral to MOD/MaaS, which "can only succeed if consumer data can be safely shared between services" (Shaheen et al. 2017a). However, data sharing leaves both users and providers of MOD/MaaS susceptible to privacy concerns and cybersecurity risks. In many cases, users may not know what data they are agreeing to have collected and shared (with the provider or third parties) when they accept terms of service for shared mobility platforms. In other instances, MOD/MaaS providers may be hacked, and this sensitive data taken. These concerns can be categorized as risks of (1) data privacy and (2) data thefts and breaches.

Data Privacy

Data privacy is a concern in cases where private, for-profit providers use personal information for their commercial needs and interests or sell personal data to a third party. However, this can pose a risk when users do not wish to share these data. Numerous studies indicate that people do not understand what information they are consenting to share or are unaware of what private information they are exposing, with many privacy policies for apps using confusing language or opaque user agreements (Shaheen et al. 2018a). In many cases, agreeing to an app's terms of service may release data to third parties. This could also apply to public agencies but has not widely been the case to date.

Data Theft and Breaches

Sharing information is critical for integrated services such as fare payment and trip planning among multiple modes, but this can increase risk. Security risks include breaches, data theft, and cyberespionage (Shaheen et al. 2020). MOD/MaaS operators and apps often track data like user origin and destination and travel times. They may "intentionally or unintentionally collect an array of sensitive and PII, such as location history, email addresses, phone numbers, financial information, usage history of the apps installed on their phone, and mobile Internet browsing history" (Shaheen et al. 2020). Vulnerabilities to data theft may exist on many different levels, such as through the app, application programming interface (API), the cloud, or hardware (Shaheen et al. 2018a). More research is needed on cybersecurity, specifically regarding what protocols could better protect MOD/MaaS systems and how to strike the balance between security and privacy (Shaheen et al. 2017a).

Agency Goal: Equity and Inclusion

With MOD/MaaS, certain groups can bear disproportionate benefits or adverse impacts, creating equity risks. For example, while increasingly becoming more widely adopted, the social characteristics and class of MOD/MaaS services users do not resemble the characteristics of the general population (Shaheen et al. 2017b). TNC customers are generally younger, well-educated, and White, suggesting that historically underserved populations are deriving fewer mobility benefits from MOD/MaaS (Martin et al. 2021). Early studies of station-based bikeshare showed that users also tend to be White, relatively young, and well-educated (Shaheen and Cohen 2019). Older adults, low-income individuals, rural communities, and minority communities have historically been less likely to use shared mobility. These groups also tend to have less access to prerequisite Internet access, smartphones, and banking services that many MOD/MaaS services require (Shaheen et al. 2017b). MOD/MaaS equity challenges include (1) possible discrimination against protected classes; (2) lack of accessibility for older adults and people with disabilities; (3) cost of MOD/MaaS (economic accessibility); (4) digital poverty; and (5) the urban and rural divide (Shaheen et al. 2017a).

Possible Discrimination against Protected Classes

Federal law protects individuals from discrimination based on characteristics, including sex, race, ethnicity, age, color, religion, national origin, and disability. Unlike state DOTs or transit agencies that receive federal funds, private MOD/MaaS providers may not be held to the same legal standard if they were to violate the rights of these protected classes (Shaheen et al. 2017a). Beyond a strictly legal framework, discrimination manifests itself as a barrier to mobility. For example, studies have found that TNCs are more likely to cancel rides for customers with names perceived to be Black (Ge et al. 2020). They take women on longer, more expensive rides and make Black customers wait longer for their rides to be accepted and to be picked up (Shaheen et al. 2017b). In summary, some modes may be deployed without requirements to consider and accommodate the needs of various protected classes.

The provision of MOD/MaaS in certain neighborhoods and its marketing to certain populations are risks for equity and inclusion. Usage demographics may be changing as shared micromobility systems incorporate flexible payment options and reduced membership fees or consider equity when establishing their zones of service. Divvy for Everyone is a bikeshare program that has an annual membership for $5.00, reducing monetary barriers to access. Social and cultural perceptions, however, still pose barriers to micromobility use for some groups (Shaheen and Cohen 2019). More research is needed to understand user demographics, especially for dockless bikeshare and scooter share (Shaheen and Cohen 2019).

The inclusion of individuals with low English proficiency or those without the ability to read may be lower because MOD/MaaS technology requires basic reading and writing skills.

Lack of Accessibility for Older Adults and People with Disabilities

The exclusion of those with mobility constraints, specifically older adults and people with disabilities, is another risk. MOD/MaaS can be difficult if the technology platform does not accommodate people with physical, cognitive, auditory, visual, or other disabilities or if legacy technology access is not maintained (Shaheen et al. 2017b; Shaheen et al. 2020). Also, MOD/MaaS operators may not provide accessible services or equivalent accessible alternatives for those with mobility limitations. For example, shared micromobility systems rarely offer hand cycles, tricycles, or other adaptive devices. Wheelchair accessible TNC vehicles (e.g., UberWAV) and specialized drivers (e.g., UberASSIST) are often unavailable even in their limited markets (Shaheen et al. 2017b). King County Metro, for example, has created a Taxi Scrip Program wherein low-income residents between the ages of 18 and 64 with a disability as well as seniors (65 years and older) can buy up to eight taxi scrips per month at a 50% discount for use with four taxi companies in the region. These scrips may be used to meet individuals' transportation needs and fill gaps in the network (Metro 2023). King County Metro also maintains a wheelchair accessible services (WAS) fund that reimburses owners and operators of wheelchair accessible taxicabs (WATs) for the higher up-front and operational costs of maintaining a WAT. Each taxi, for-hire vehicle, and TNC pays a WAS surcharge for all rides (KingCountyMetro.gov 2023).

Economic Accessibility

The cost of MOD/MaaS (i.e., economic accessibility) is another equity and inclusion risk. MOD/MaaS providers often require users to have access to a credit or debit card for registration or payment, hindering use by those who rely on cash. A 2021 Federal Deposit Insurance Corporation survey found that 4.5% of U.S. households were unbanked (no one in the household had a checking or savings account) and 14% were underbanked (Federal Deposit Insurance Corporation 2021). Even for banked individuals, MOD/MaaS services may be more expensive compared to other modes (e.g., walking, transit) or require unaffordable up-front subscription payments. In particular, the use of surge pricing during peak times by TNCs can make this mobility option unrealistic for lower-income populations (Shaheen et al. 2017b).

Digital Poverty

Because of its heavy reliance on smartphones and mobile Internet for trip planning, reservations, and payment, MOD/MaaS risks creating disparities between those with and without digital access. This is known as "digital poverty" or the "digital divide." Lack of Internet access is a challenge among those over the age of 65, with incomes below $30,000, without a high school diploma, and those living in rural areas (Shaheen et al. 2017a). The main reasons for not going online include lack of interest, lack of relevance to their lives, difficulty using, and costs (Shaheen et al. 2017a). Furthermore, because they lack Internet access, these populations tend to have lower rates of smartphone usage (Shaheen et al. 2017a; Shaheen et al. 2020). This is a major equity concern of MOD/MaaS because those populations, who could benefit from time savings and the convenience of MOD/MaaS services, do not (Shaheen et al. 2017a).

The Urban and Rural Divide

The urban and rural divide is in part due to the digital divide, since rural mobile service and high-speed data may be more limited, making access to shared mobility services that require Internet access and smartphones more difficult (Shaheen et al. 2017b). However, MOD/MaaS may also be unequally provisioned because of its providers' focus on dense urban areas with larger customer bases and higher demand. Privately operated shared mobility services, which need to achieve full cost recovery (or make a profit) to remain operable, may limit the deployment in lower-density and low-income communities (Shaheen et al. 2017b). The ability for providers to operate in a cost-effective and profitable manner in urban areas leads to service improvements there while leaving rural areas with fewer and lower-quality options (Shaheen et al. 2017a). This risk is not unique to MOD/MaaS; the "logistical and financial constraints that impact mass transportation systems typically affect shared mobility services" (Shaheen et al. 2017a).

Barriers to transportation equity have been described by experts as having five dimensions. The STEPS framework is used for thinking about the following five dimensions of transportation equity: spatial, temporal, economic, physiological, and social. Spatial factors may limit accessibility due to, for example, long travel distances or the lack of public transit within walking distance. Temporal factors limit one's ability to complete time-sensitive trips due to, for example, transit reliability challenges or congestion levels. The economic component describes mobility challenges faced due to direct and indirect costs that create financial hardship or lead individuals to forgo making a trip. Physiological elements include the physical or cognitive limitations that make it more difficult for individuals to complete trips. The social element refers to social, cultural, or language barriers that limit a user's comfort using transportation (Shaheen et al. 2017b). Because MOD/MaaS seeks to make more forms of transportation available to the community, users can select the mode that is most suitable for them given their unique needs and limitations, thereby creating a more inclusive system.

Agency Goal: Public Health

MOD/MaaS is most widely understood as a benefit to public health by increasing the use of active modes, such as bicycle usage and walking. For example, a study of station-based bikesharing in Oregon found an increase in physical activity among users. An assessment of Portland's 4-month pilot of standing electric scooter sharing found that scooter sharing attracted new people to active transportation (Shaheen et al. 2020).

Agency Goal: Acceptance

Public acceptance and willingness to adopt MOD/MaaS, or lack thereof, poses another risk. Acceptance is related to and intertwined with the equity and inclusion risks described previously, but it can be distinguished by personal choice and the individual decision-making involved, as opposed to structural barriers (such as economic or digital access). Acceptance can be influenced by (1) personal preferences and (2) perceived safety.

Personal Preferences

Those who use MOD/MaaS tend to be well-educated, younger, childless, middle to upper middle class, and living in locations with multiple alternatives to personal vehicles (Shaheen and Cohen 2019). As a result of both the digital divide and personal preference, acceptance of certain MOD/MaaS services by older populations (e.g., bikeshare) may lag that of the general population because of unfamiliarity with using the required technology. In contrast, people who have grown up with wide usage of technology and the Internet "make up an increasing proportion of the workforce and society at large . . . [and] tend to accept and even expect [information and communications technology] integration into their lives" (Shaheen et al. 2017b).

Acceptance is also affected by preferences for driving personal vehicles, especially in lower-density areas where MOD/MaaS services are less competitive (i.e., where land use discourages acceptance and overall demand) (Shaheen et al. 2020). In the United States, many drive alone out of necessity due to the constraints of the built environment and limited modal choices. Although cultural norms of ownership and unlimited consumption will continue to influence the acceptance of MOD/MaaS, attitudes may shift with time (Shaheen et al. 2017b). For example, a study of 11 U.S. cities found that 70% of respondents support micromobility, viewing standing electric scooter sharing as a convenient form of mobility without the hassle of owning a car" (Shaheen et al. 2020).

Perceived Safety

Even before health concerns prompted by COVID-19, acceptance of pooled TNC rides was shaped by perceptions of safety. Passengers who were comfortable interacting with drivers (presumably screened in the hiring process and distanced in the front versus back seat) may have been less comfortable with fellow riders who did not have the same screening (Martin et al. 2021).

Agency Goal: Sustainability and Environment

MOD/MaaS is associated with mixed outcomes related to sustainability. Usage of MOD/MaaS is sustainable in that it can facilitate low- or no-emission micromobility as an alternative to personal vehicle trips (Shaheen et al. 2020). These outcomes must be balanced, however, by sustainability impacts associated with rebalancing, manufacturing, recycling, and replacing micromobility devices and batteries (Shaheen et al. 2020). While in some cases, reducing VMT, MOD/MaaS (particularly TNCs) also have the potential to increase congestion or pull riders from public transit—leading to more VMT and harmful GHG emissions.

Pollution/GHG Emissions

Carshare generally does not lead to sustainability risks. A study of one-way carsharing (car2go) in five North American cities found that the service was, overall, reducing car ownership, driving, and GHG emissions (Martin and Shaheen 2016). Though many car2go members drove more, this was outweighed by the impact of a smaller number of members that either sold their personal vehicles or avoided purchasing one. The study estimated that the VMT of car2go households changes by –6% to –16% and their GHG emissions by –4% to –18%. Another study of carsharing members across North America in 2008 explored how on-demand access to a shared vehicle can increase driving by the previously carless. It found an overall reduction in annual emissions, despite the majority of households increasing their emissions in small amounts (Martin and Shaheen 2011). Despite the overall benefits of carsharing, "not all members reduce emissions," impacts may be geographically specific, and the benefits may be overstated due to inactive members.

MOD/MaaS services involving TNCs have a less clear beneficial outcome. In a study of TNC impacts in San Francisco, Los Angeles, and Washington, DC, researchers found that Uber and Lyft use resulted in a net decrease in VMT and GHG emissions in Washington, DC, but a net increase in the California cities, possibly due to land use patterns (Martin et al. 2021). What mode TNC customers shift from influences the sustainability of TNC use; taxi was the most common way respondents would have traveled without TNCs in all three cities, but the next most common shift was from transit in San Francisco and Washington, DC (versus personal vehicles in Los Angeles). Research also suggests that TNCs draw more passengers from transit than they add to it via first-/last-mile connections (Martin et al. 2021). Only 2% or fewer of study respondents used TNCs to connect to transit that otherwise would not have taken transit. More (5% to 11%) would have connected to transit anyway or used transit instead of Uber or Lyft (19% to 34%).

TNCs can lead to increased VMT and associated GHG emissions due to deadheading (trips without passengers) and trips themselves (with passengers) (Shaheen et al. 2020). Also, pooled TNC operations do not affect overall VMT and GHG emissions (Martin et al. 2021).

Agency Internal Goal: Workforce Development

MOD/MaaS presents workforce-related risks. The rise of the sharing economy has disrupted traditional economic models, as private individuals commercialize previously private-use assets such as cars (Cohen and Shaheen 2016). However, while MOD/MaaS shared mobility services have increased employment opportunities, they have also contributed to downward wage pressures (when considering hourly wages, app fees, contractor status, and worker benefits). Further regulation may be needed to protect workers' rights and limit risks of (1) lack of a trained workforce and (2) worker exploitation.

Lack of Trained Workforce

Labor trends specific to MOD/MaaS could include more demand for positions such as data scientists or personnel that rebalance/recharge micromobility devices, or retraining of existing staff (Shaheen et al. 2020). This is a risk because public agencies especially may lack the human or technical resources to accommodate and oversee MOD/MaaS operations and initiatives (e.g., analyzing big data generated by mobility providers) (Shaheen et al. 2020).

Worker Exploitation

In addition to MOD/MaaS affecting jobs by sector, it is also disrupting workforce practices. MOD/MaaS often relies on gig workers (part-time, flexible schedule, independent contractors) who are less likely to have benefits and living wages (Shaheen et al. 2020). While most transit agency employees are unionized and have protected worker rights, TNC drivers are considered contract workers with little influence on their employment conditions (Iglitzin and Robbins 2017). The hiring practices of MOD/MaaS providers, specifically the classification of workers as independent contractors, can have implications for driver compensation, taxes, and benefits (Shaheen et al. 2020). Furthermore, some studies have revealed that these drivers may be making less than minimum wage per hour due to fees, fares, and payment structures from service providers (e.g., drivers are not paid for the time they spend on the app without a customer, or for the time it takes to travel to a waiting customer—"deadheading") (Scheiber 2020).

More research on the fair compensation of TNC drivers could be beneficial because regulatory landscapes are continuously evolving and conclusions of studies on the topic vary (Scheiber 2020). As has been seen with TNCs, worker exploitation can occur, indicating fair compensation issues may exist with other modes present in the MOD/MaaS platform.

MOD/MaaS Risk Register by Risk Priority

The risk register of potential sources of risk from MOD/MaaS is presented in a pair of tables: Tables 5.1a and 5.1b. Table 5.1a provides information typically found in a standard risk register (while applying the exceptions discussed in Chapter 2). This table presents its rows in descending order of assessed risk priority. Table 5.1b provides data that underly the calculation of both forms of the LOC measure, the SI-LOC and CB-LOC (see Chapter 2). These data are useful for raising awareness within the agency of the relevant aspects of a source of risk from emerging and disruptive technologies to agency goals. Therefore, each pair of tables provides more detail than is typical of standard risk registers to present the underlying methodology so that agencies can make modifications that will support their own deliberations and risk prioritization. The full methodology for doing so is found in Appendix C.

The same data appearing in Tables 3.2a, 4.1a, 5.1a, and 6.1a are presented in Appendix B sorted by agency goal.

Tables 5.1a and 5.1b are followed by a review of the literature on potential hazards (sources of risk) connected with MOD/MaaS.

Table 5.1a. Risk register by risk priority for MOD/MaaS technology group.

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
M1 Air Pollution and GHG Emissions	Pollution/GHG emissions	1. GHG calculated by VMT on MOD services. 2. Localized GHG calculated by usage.	3	Sustainability	Increased GHGs and localized pollution from MOD services.	**2**	1. State guidelines on what percentage of the fleet must be ZEVs each year. 2. Rules on when all MOD/MaaS vehicles must be zero emission. 3. Identification of power source for EV charging.	State DOTs, local DOTs.	**Moderate-High**
M2 Road Crashes	Road crashes	1. Crash data. 2. Fatal crash data.	3	Safety	Increased transportation crashes (and associated injuries/deaths).	**2**	Geofencing for high-conflict locations to slow or stop usage. Design and speed limit policy (e.g., “20 is plenty”).	State DOTs and MPOs work with local governments on policy and mitigation.	**Moderate-High**
M3 Inequitable Access	Lack of accessibility	Services or the number of vehicles do not meet demand for those with disabilities at a rate like those without disabilities. Some services (e.g., micromobility) are launched without addressing universal access.	2	Equity	Only populations with full abilities can access the full suite of MOD options.	**2**	1. Identifying minimum standards for availability of accessible vehicles. 2. Creating a mobility fund to provide services for those with disabilities.	Providers, state DOTs, and local DOTs.	**Moderate**
M4 Discrimination	Discrimination against protected classes	Affordability of MOD services among all classes and income levels.	3	Equity	Limited access. Little/no access for populations that have been made vulnerable.	**1**	1. Identifying circuit-breaker programs to ensure affordability for all classes and abilities.	MPOs and DOTs; social equity and justice organizations.	**Moderate**

(continued on next page)

Table 5.1a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
M5 Exploited Workforce	Exploited workforce	1. Workers are not making a living wage. 2. Workers fall below the average median income for full-time work.	2	Workforce	1. Potential for unsafe operations if workers need to have multiple jobs.	**1**	Set regulations to ensure fair wages are established.	Legislature workforce/ business affairs.	**Low**
M6 Data Theft and Breaches	Data theft and breaches	Data breaches that diminish MOD/MaaS mode share. Data breaches affect service delivery for MOD/MaaS.	1	Security & Privacy/ Safety	User security is compromised.	**2**	Develop robust data security systems for system protection. Develop regulatory requirements to ensure providers are reporting breaches and their impacts regularly.	CISA; business affairs agencies with support from DOTs.	**Low**
M7 Increased Congestion	Increased traffic congestion	Related congestion data (e.g., Inrix, telematics).	1	Mobility	Risks of TNCs replacing high-occupancy modes and induced demand for MOD services.	**2**	Identify incentives for sustainable modes and caps on TNC trips at peak times.	State and local DOTs in partnership with MOD providers.	**Low**

CISA: Cybersecurity and Infrastructure Security Agency.

Source: RAND and Sam Schwartz

Table 5.1b. Elements of two likelihood proxies and overall results for MOD/MaaS technology group.

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Infor-mation	Response		Metric	Target	Tolerance Level (+/-)				
M1 Air Pollution and GHG Emissions	1	1	3	2	2	1	GHG emissions.	Lead to reductions in GHG emissions and region meets climate targets set by the Paris Agreement and local climate goals.	0.1	Out of Tolerance	Negative	3	3
M2 Road Crashes	2	2	2	3	3	3	1. Crash data. 2. Fatal crash data.	MOD should be within 10% of the fatality rate for transit (289 occupant, worker, and other deaths reported in 2020 by the Bureau of Transportation Statistics).	0.05	Out of Tolerance	Negative	3	3
M3 Inequitable Access	2	1	3	2	2	2	Affordable and accessible to people across all ability levels.	There should be options on a MOD platform that meet transit accessibility standards.	0	On Target	Negative	2	2
M4 Discrimination	1	1	3	2	3	3	Affordability of MOD services among all classes and income levels. It is well known that MOD is utilized most by younger, higher-income, educated individuals. Metrics may include pricing per ride; geographic distribution of service.	Use the region's area median income to develop a threshold for where service becomes unaffordable.	0	Out of Tolerance	Negative	3	3
M5 Exploited Workforce	2	2	2	2	3	3	Hourly wage and number of hours needed per week to make a living wage.	Consistent with bus drivers' earnings; hourly wage threshold set by TNC minimum compensation ordinances.	$15 minimum wage threshold	Out of Tolerance	Positive	2	2
M6 Data Theft and Breaches	2	1	2	3	2	2	1. Data breaches that diminish mode share and affect service delivery. 2. Number of crashes or injuries from data breaches.	Goal of zero.	0.1	On Target	Positive	1	1
M7 Increased Congestion	2	2	3	3	3	3	Congestion leads to increased travel time when comparing times during free flow.	Incremental improvement of travel times during peak periods.	50% Slow down	On Target	Positive	1	1

Source: RAND and Sam Schwartz.

CHAPTER 6

Risk Register and Risk Priorities for Advanced Air Mobility (AAM)

This chapter presents the risk register that resulted from applying the method outlined in Appendix C to the input received from a literature review and the results from the peer exchanges. We first present a synopsis of a review of the literature on agency risks associated with deployment of AAM. The risk register necessarily requires concise language for presentation. By first presenting several of the literature review findings, the report will help readers gain fuller benefit from the risk register that then follows.

Literature Review on AAM Sources of Risk

State of AAM

What Is AAM?

AAM is a broad concept focusing on emerging aviation markets and use cases for on-demand aviation in urban, suburban, and rural communities. AAM includes local use cases of about a 50-mile radius in rural or urban areas and intraregional use cases of up to a few hundred miles that occur within or between urban and rural areas. AAM includes passenger mobility, goods delivery, and emergency services in urban and rural areas (commonly referred to as UAM and rural air mobility, respectively) (Cohen et al. 2021; Reiche et al. 2018).

In recent years, on-demand aviation services similar to TNCs have been entering the marketplace. In the early 2010s, on-demand, app-based aviation services began entering the marketplace. In New York City, BLADE, launched in 2014, provides helicopter services booked through a smartphone app. BLADE uses third-party operators that own, manage, and maintain their aircraft (Cohen et al. 2021).

A variety of technological advancements and industry investments in electrification, automation, VTOL aircraft, UAS, and unmanned aircraft system traffic management (UTM) are enabling innovations in aviation such as new aircraft designs, services, and business models. Several companies have announced plans to launch passenger AAM services using VTOL and other novel aircraft designs anticipated in the mid- to late-2020s. A few prepandemic market studies estimate the potential for scaled operations and profitable services in the late-2020s and early 2030s (Porsche Consulting 2018; Morgan Stanley Research 2019; Cohen et al. 2021; Reiche et al. 2018; Goyal et al. 2021; Hasan 2019). As an emerging concept, AAM presents several risks to growth, adoption, and mainstreaming such as equity; privacy and data security; public acceptance; safety (e.g., air traffic management, weather, security); and sustainability and environment (e.g., noise and visual pollution) (Cohen et al. 2021). Each of these risks is discussed in greater detail in the sections that follow.

Agency Goal: Equity

While limited published research exists on the potential equity impacts of AAM, the impacts of AAM on populations that have been made vulnerable is considered a highly probable risk with potentially significant impacts. Many social equity concerns focus on environmental justice considerations related to the fair treatment of all people regardless of race, ethnicity, color, national origin, or income concerning the planning and implementation of AAM services, policies, and regulations. Fair treatment means no group of people should bear a disproportionate share of the negative environmental consequences resulting from public or private-sector operations or policies (U.S. EPA n.d.).

For AAM passenger use cases, current services using helicopters are premium offerings that have, in recent years, typically averaged $149 to $300 US per seat (Cohen et al. 2021). Duffy et al. (2017) estimate that eVTOLs will reduce total operating cost per seat mile by about 26% (compared to helicopters currently in use). Porsche Consulting estimates that on-demand air taxis will cost $8 to $18 US per minute (Porsche Consulting 2018). McKinsey and Company estimate that an "air metro" service within a metropolitan region will cost $30 US per trip in 2030, while air taxis will remain higher, ranging from $131 to $1,912 US per trip (depending on vertiport density) (Hasan 2019). There are concerns that AAM may not be an affordable transportation option for lower- and middle-income households and that AAM may be used by upper-income households to bypass surface congestion. While proponents compare AAM to early commercial aviation and the eventual democratization of air travel, it took decades for commercial aviation to achieve mass-market affordability (Cohen et al. 2021). Additionally, the business models of intraurban, small aircraft operations are quite different from general and commercial aviation. While electrification and automation have the potential to reduce costs, it is unclear if AAM can be affordable for a mass market. Similar concerns could also be raised with the affordability of some emergency response use cases, such as medical transport (e.g., people without any or sufficient levels of medical insurance coverage may not be able to afford aeromedical transport or be left with unaffordable medical transportation bills after using the service) (Goyal and Cohen 2022). Ensuring accessibility for people with disabilities is also another concern.

There are also concerns that low-income, minority, and other populations that have been made vulnerable may bear a disproportionate share of the negative environmental impacts of AAM (Cohen and Shaheen 2022). While not an exhaustive list, examples include the impacts of flight paths (i.e., noise) on low-income and minority neighborhoods and concerns about gentrification and displacement around vertiports. Public agencies should also consider that equity concerns may exist regarding public-sector investments in AAM, and if such investments are diverting funding from other services with broader availability (e.g., public transportation). The public sector can play a key role in guiding equitable outcomes by ensuring full and fair participation in AAM decisions that may affect their environment or health, and by applying environmental justice principles to the review and approval of vertiport locations and flight paths. Public agencies may also support equitable outcomes through various pricing models, subsidies, and programs that expand AAM access to low-income populations and those that have been made vulnerable, which may mitigate some of these equity concerns.

In summary, there is a lot of uncertainty about how much AAM will ultimately cost, how long it will take to become affordable (if ever), what type of public investment (if any) should support AAM, and what will be the impacts of AAM users on nonusers (i.e., noise, aesthetics, vertiport sighting, foregone public-sector resources that could be spent on other initiatives, etc.). Ensuring meaningful involvement and fair treatment of all people in AAM planning and implementation will be critical.

Agency Goal: Privacy and Data Security

Source of Risk: Privacy

Physical and data privacy represent another potential risk of AAM. For example, residential communities may have privacy concerns about low-altitude aircraft flying over homes and yards (as well as other impacts). While studies on the potential privacy impacts of AAM are limited, some emerging studies on UAS/drone privacy may provide some insight. Drones are capable of highly advanced surveillance and are already used by law enforcement. They may be equipped with various types of equipment, such as live-feed video cameras, infrared cameras, heat sensors, and radar, potentially raising several concerns associated with privacy and civil liberties. Several qualitative and quantitative studies examining the perception of bystanders about drone privacy have found that the public has notable concerns relating to stalking, photo/video recording, the sharing of recorded information, and the use of drones near residential land uses (Wang et al. 2016; Rice et al. 2018; Winter et al. 2016; Uchidiuno et al. 2018; Bajde et al. 2017). In contrast, a study by Yao et al. (2017) which studied privacy concerns from the perspective of UAS/drone controllers found that most drone operators believed that privacy concerns were exaggerated and that drone operators have the Constitutional right to fly drones in public spaces (Yao et al. 2017).

Other studies suggest regulation has not kept pace with the potential technological and privacy concerns associated with drones (Winkler et al. 2018; Jenkins 2013; Ljungholm 2019). However, some states have begun to pass legislation intended to protect the privacy rights of individuals from aerial surveillance. For example, California's Assembly Bill 856, which was ratified in 2015, allows a person to be liable for the physical invasion of privacy when that person knowingly enters the land or airspace above the land of another person without permission to capture a visual image or sound recording. The likelihood and severity of physical privacy risks will vary based on a variety of factors such as aircraft configuration (e.g., the ability for owners to outfit their aircraft with equipment that can collect sensitive information), operational characteristics (e.g., the altitude and flight paths of AAM operations), and operational tempo (e.g., overall volume and intensity of AAM operations over a particular area).

Additionally, there are several privacy concerns associated with data collection, sharing, and management (e.g., user, financial, location, trip data). Broadly, the majority of these data concerns center on traveler or user privacy. However, there could also be privacy concerns from the private-sector perspective associated with the sharing and storage of data and its potential impacts on proprietary trade secrets. Estimating the likelihood or potential severity of this risk will likely depend on a variety of factors such as compliance with data security standards and regulations governing handling and management of sensitive data.

Agency Goal: Public Acceptance

Unlike other risks associated with AAM, community or public acceptance is both a risk and an outcome of other AAM risks. Negative community perceptions could pose challenges to the adoption and mainstreaming of AAM (Cohen et al. 2021). A few notable concerns that will likely contribute to public acceptance include safety, noise, visual pollution, privacy, equity, and other social and environmental impacts. Many of these topics are discussed in greater detail throughout this chapter. While several exploratory surveys have attempted to understand barriers to community acceptance, the lack of public experience with AAM aircraft and scaled operations represents notable limitations of these studies (Yedavalli and Mooberry 2019; Shaheen et al. 2018b; Holden and Goel 2016; Fu et al. 2019). In November 2019, the Community Air Mobility Initiative, a nonprofit, was established to educate and provide resources to the public and local, state, and provincial decision-makers. Ongoing education, outreach, community engagement, and research are needed to advance the understanding of potential barriers to community acceptance and policies that will be able to guide safe, sustainable, and equitable outcomes.

Agency Goal: Safety

Aviation safety is supported by a robust federal policy and regulatory environment governing aircraft and airworthiness; operations (including crew requirements); and access to airspace (Graydon et al. 2020; Thipphavong et al. 2018). Civil aviation authorities have tools such as certification, operational approvals, and airspace access to promote safety. This regulatory scope provides a toolbox of approaches that civil aviation authorities can use to manage and promote the safety of all stakeholders. Additionally, state and local governments can promote safety through land use and zoning, building and fire codes, and law enforcement operations (Cohen et al. 2021).

Valid concerns about the safety of AAM users, other airspace users, and bystanders (i.e., people flown over on the ground) could present safety risks and barriers to adoption (Cohen et al. 2021; Graydon et al. 2020; Thipphavong et al. 2018). Safety risks from AAM relate to aircraft and the operational environment (Connors 2020). Nine systemwide, safety-critical risks that will need to be addressed include the following:

- Ground safety, including aircraft access/egress and ground operations.
- Flight outside approved airspace.
- Unsafe proximity to people or property.
- Critical system failure (e.g., degraded or loss of command and control; GPS; engine failure).
- Loss of control (e.g., flight control system failure).
- Fires associated with fuelig, charging, and energy systems.
- Cybersecurity risks.
- Hull loss.
- Other potential hazards such as weather, birds, air and ground crew human factors (i.e., loss of situational awareness, task saturation), and passenger interference (i.e., disruptions, hijacking, sabotage, etc.).

Flight safety is evaluated by the interaction of three characteristics or conditions: (1) criticality of the function; (2) severity of a failure; and (3) probability of an event, with criticality of the function and severity of a failure being overlapping concepts (Connors 2020). These concepts are summarized in Table 6.1.

Connors (2020) explains that assessing the severity and probability of an individual failure is relatively straightforward; however, the emergence of complex and automated systems is resulting in the need for more advanced risk assessment techniques. Connors (2020) further points out that quantitative safety measures are increasingly being complemented with qualitative measures. Qualitative metrics identified by Connors (2020) include the following:

- Extremely Improbable. A failure condition is not expected to occur during the entire operational life of all airplanes of this type.
- Improbable or Remote. A failure condition is not anticipated to occur during the entire life of a single random airplane. However, a failure may occur occasionally during the entire operational life of all airplanes of one type.
- Probable. A failure condition is anticipated to occur one or more times during the operational lifetime of each aircraft.

According to Connors (2020), "An acceptable safety level for equipment and systems is based on an inverse relationship between the average probability of failure per flight hour and the severity of the failure condition being considered. Critical aircraft functions are required to

Table 6.1. Flight safety evaluation characteristics.

Criticality	Nonessential. These functions are those that do not contribute to or cause a failure condition which would be significantly deleterious to the safety of the airplane or the ability of the flight crew to cope with adverse operating conditions.
	Essential. Essential functions are those that could contribute to or cause a failure condition that would significantly affect the safety of the airplane or the ability of the flight crew to cope with adverse conditions.
	Critical. Critical functions are those whose failure would cause a condition that would prevent the continued safe flight and landing of the airplane.
Severity	Failure with no safety effects. Minor failure conditions. Major failure conditions. Hazardous failure conditions. Catastrophic failure conditions.
Probability	Extremely improbable (1×10^{-9} or less). Failure would be expected to occur no more than once in a billion hours of flight.
	Improbable or remote (1×10^{-5} or less). Failure would be expected to occur no more than once in 100,000 hours of flight.
	Probable (1×10^{-5} or more). Failure would be expected to occur more than once in 100,000 hours of flight.

Source: Adapted and reprinted from Connors (2020).

be Extremely Improbable. Essential functions are required to be Improbable; while nonessential functions have no specific probability requirements."

Under the current regulatory regime, standards exist only for onboard piloted operations. The legal, policy, and regulatory environment may present challenges for certifying and authorizing the use of some novel technologies and combinations of features that could be found in AAM aircraft (Connors 2020; Coudert et al. 2019; Reiche et al. 2018). While not an exhaustive list, some of the safety risks associated with novel AAM technologies include distributed electric propulsion/tilt-wing propulsion, VTOL, autonomy hardware and software, optionally piloted configurations, electric energy storage, and others (Coudert et al. 2019; Reiche et al. 2018). Additional safety challenges for emerging aviation technologies can include the following:

- Autonomy and Highly Complex Software. Machine-learning and other algorithms are nondeterministic, which means that even for the same input, the algorithm may exhibit different behaviors on different runs (Reiche et al. 2018).
- Electric Propulsion and Energy Storage. Both propulsion and energy storage may pose a variety of challenges. More research is needed to understand a variety of risks associated with aircraft electrification (Reiche et al. 2018).
- Uncrewed and Optionally Piloted Aircraft. For AAM aircraft to operate automatedly, there are several operational risks, such as physical security, operational procedures, cybersecurity, and traffic management that will need to be considered as part of airworthiness (Reiche et al. 2018).
- Ratio of Aircraft to Operators Less Than 1. Several AAM business models involve a transition period to full autonomy that may include operations centers with remote operators controlling multiple aircraft. The associated operational risks will need to be considered as part of airworthiness certification, airspace access, crew training, certifications, and operational approvals (Reiche et al. 2018).

The NTSB is an independent federal agency authorized by Congress to investigate every civil aviation incident in the United States (as well as other significant incidents involving other modes of transportation). Longitudinal safety data from the FAA shows that air carriers operating under 14 CFR 121 (i.e., commercial airlines) have the fewest number of crashes and fatalities, followed by air carriers operating under 14 CFR 135, with the highest number of incidents and fatalities reported by general aviation. The key takeaway is that while aviation has historically had a relatively good safety record compared to other modes, its safety record varies considerably when comparing specific categories of operations. There are likely many factors for this such as regulations, policies/procedures, aircrew training, and aircraft types. Because AAM is an emerging technology, the regulatory environment and how AAM aircraft, personnel, and air carriers are certified and regulated are likely to evolve. As such, it is not possible to forecast how safe AAM will be compared to other aviation services or other transportation modes. What is clear is that while the public and private sectors are committed to a vision of zero incidents and fatalities, the risk of an incident is almost certain. The NTSB Office of Aviation Safety investigates all civil domestic air carrier, commuter, and air taxi incidents; in-flight collisions; fatal and nonfatal general aviation incidents; and certain public-use aircraft incidents. It also conducts investigations of safety issues that extend beyond a single incident to examine specific aviation safety problems from a broader perspective (NTSB 2021). However, the ability to identify early indicators of AAM safety-related trends may be dependent on how AAM safety incidents are indexed and monitored. For example, in the early years of AAM deployment, a low number of flight hours with a comparatively high number of safety incidents involving novel AAM aircraft may not be readily identifiable under existing reporting tools if combined with other Part 135 operations (of note Part 135 operations accounted for 3.26 million flight hours in 2020). As such, state DOTs and federal agencies could consider tracking safety incidents involving specific aircraft designs and technologies to aid in early identification of emerging safety risks and trends. Examples of categories that state DOTs (and other agencies) may consider tracking include AAM safety incidents involving the following:

- Piloted, remotely piloted, and automated AAM aircraft.
- Vertical, short, and conventional takeoff and land aircraft (VTOL, STOL, and CTOL, respectively).
- Aircraft configuration (e.g., multicopter, lift+cruise, vectored thrust, augmented lift, and other design categories).
- Propulsion type (e.g., gas-powered, electric, hydrogen).
- Use case (e.g., passenger services, cargo delivery, emergency response).

A high incident or fatality rate involving AAM would reduce safety and could present related risks such as increasing the likelihood of litigation, increased insurance costs, or a service provider's canceled insurance. However, a low incident or fatality rate could reduce these risks and encourage public acceptance and user adoption of AAM. In some cases, the level of risk is not only dependent on the safety rates of AAM but also on the impact of these incidents on bystanders on the ground (Connors 2020). Given that it is anticipated AAM will operate in complex operational environments (e.g., low-altitude airspace over predominantly urbanized areas), even a low number of safety incidents could present a notable risk if such incidents involve a loss of life or property. In a worst-case scenario, a poor safety record could have a notable impact on public agencies (e.g., legislative hearings, loss of public trust and confidence).

While the FAA will remain the primary regulatory authority for aircraft and airworthiness, operations, and airspace, state DOTs play an important role in several key areas. For example, state DOTs generally administer state and federal funds for airport development, maintenance, and operation. They also regulate, inspect, and license aviation operations. They may also support safe flight through radio and visual navigation aids; electrical and lighting systems; and collect and disseminate weather information to aircrews. State DOTs can support AAM safety through the following:

- Educational and research safety programs.
- Grants and funding of airport and other AAM infrastructure improvements intended to improve safety.

- Registration of aircraft and aircrew in accordance with state laws and regulations.
- Inspections of public- and private-use facilities to ensure compliance with state and federal regulations.
- Wildlife management and security at and near airfields.
- Facilitating search, rescue, and recovery operations when safety incidents occur.
- Partnering with the NTSB, FAA, and TSA on safety-related roles.

Source of Risk: Air Traffic Management

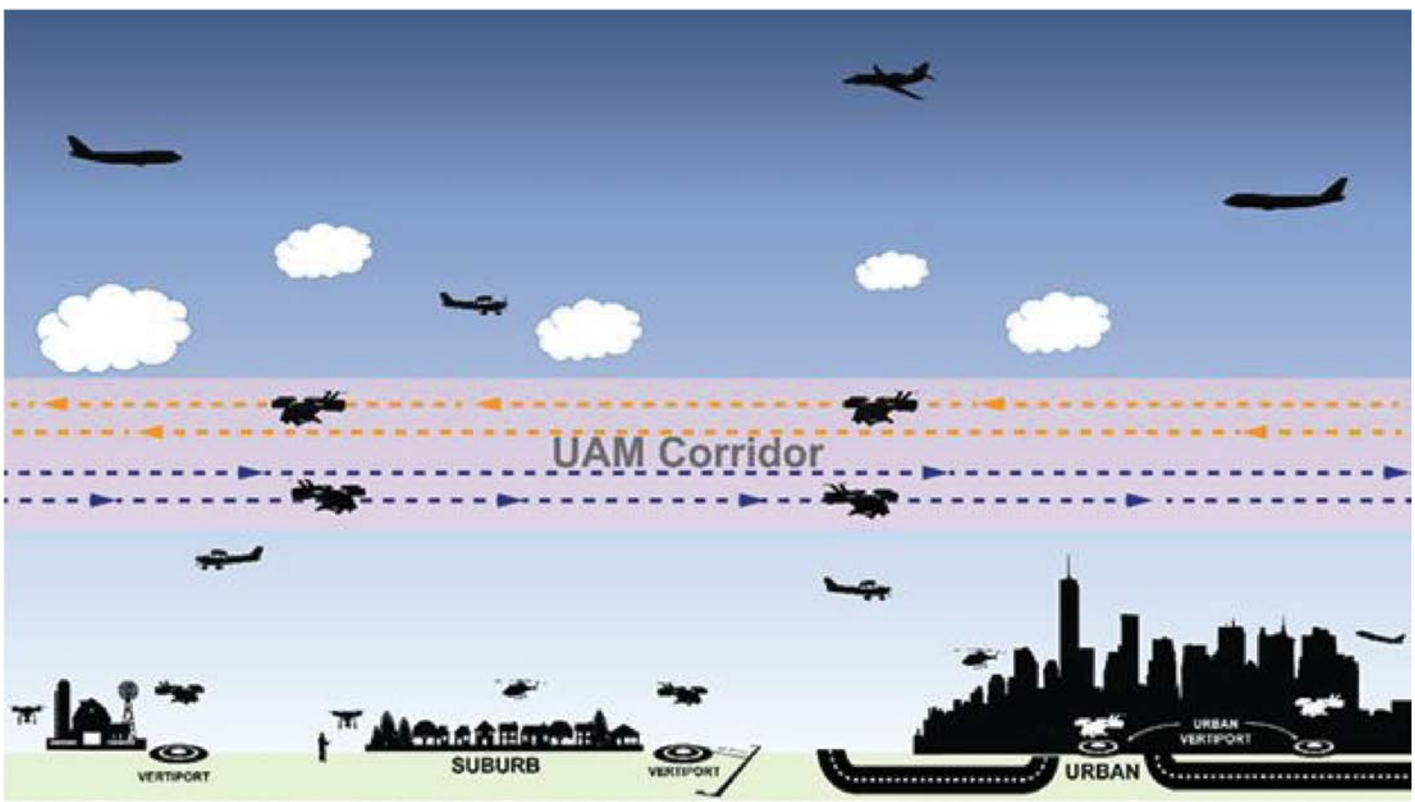
AAM operations are expected to take place at relatively low altitudes and in dense urban environments as part of several envisioned use cases (Cohen et al. 2021). One of the principal challenges with AAM is that it will likely have to interact with existing commercial aviation and UAS ecosystems in a variety of contexts. Part 121 commercial air carriers operate with experienced pilots in controlled airspace where air traffic controllers have the authority to direct air traffic. In contrast, Part 107 UAS/drones have generally evolved in low-level and uncontrolled airspace using a different set of regulations, often with relatively inexperienced operators. AAM services operating in urban areas (particularly to/from large and medium airports) will have to interact with both of these operational environments and likely fly in both controlled and uncontrolled airspace. Additionally, AAM will also need to ensure safe takeoff, approach, and landing alongside drones that typically operate below 400 feet (FAA 2018). These interactions present several interrelated air traffic management-related risks, including safety, deconflicting and prioritizing users of shared airspace, and air traffic congestion as the operations tempo of AAM activity increases.

Controlled airspace is found around some airports and at certain altitudes where air traffic controllers are actively communicating with, directing, and separating all air traffic. Controlled airspace consists of five tiers beginning with most restrictive to least restrictive: Class Alpha (A), Class Bravo (B), Class Charlie (C), Class Delta (D), and Class Echo (E). Other airspace is considered uncontrolled (Class G) in the sense that air traffic controllers are not directing air traffic within its limits. The ability for AAM to transition from either uncontrolled Class G airspace or designated AAM airspace corridors to busy controlled airspace (i.e., Class B) without overwhelming air traffic control is one key risk. Additionally, procedures will need to be established for resolving collision avoidance alerts, particularly between AAM and commercial (Part 121) aircraft. As the number of operations increases, collision avoidance, communication, and management systems of both AAM and non-AAM airspace users may need to adapt (Graydon et al. 2020; Neogi and Sen 2017).

The risks AAM presents to air traffic management may vary based on external factors such as the size and growth of the industry; composition of piloted, remotely piloted, and automated flight operations (including whether these operations can coexist within the same airspace); enabling air traffic technologies such uncrewed aircraft system traffic management (UTM); and use cases adopted (Graydon et al. 2020; Neogi and Sen 2017). Due to the complexity of low-altitude urban airspace, UAM use cases will likely present a greater degree of risk associated with air traffic management than rural operations. However, even in urban areas, air traffic management risks will likely vary based on local and regional factors such as existing airspace classes and congestion, location, and proximity of major airports to AAM operations, and other factors. As such, it is not possible to forecast the level or likelihood of air traffic management risk.

The Federal Aviation Act of 1958 delegated the safe and efficient use of the airspace to the FAA, requiring it to create and enforce federal regulations (Serrao et al. 2018). Under existing laws and regulations, the FAA has exclusive authority over the national airspace. In recent years, the FAA has taken steps to manage risks related to AAM air traffic management. In March 2020, the FAA released the UTM Concept of Operations 2.0, which seeks to address more complex airspace operations for UAS operating at or below 400 feet above ground level and increasingly more complex operations within and across controlled and uncontrolled airspace (FAA 2020a). Additionally, the FAA has published the Urban Air Mobility Concept of Operations (ConOps) v2.0, which describes the envisioned operational environment to support the anticipated growth of flight operations in and around these urban areas (FAA 2023). The ConOps presents the FAA's air traffic management vision to support initial AAM operations in urban and suburban environments. The ConOps envisions that initial AAM operations will comprise a small number of low-complexity operations and will evolve to mature state operations with a high density and high rate of complex operations. As the operational tempo of AAM increases, the ConOps envisions the establishment of "UAM corridors" where piloted aircraft will have the capability to exchange information with other corridor users to deconflict traffic without relying on air traffic control (FAA 2023). Figure 6.1 illustrates the different environments and types of operations in each environment. UAM corridors are shown in yellow along with airports (and other takeoff and landing infrastructure) supporting UAM operations (FAA 2023).

The ConOps also envisions the establishment of "providers of services for UAM" (PSUs) to support operations planning, operational intent (e.g., flight plans), airspace management, and information exchange during operations. The ConOps envisions that PSUs would process flight requests; evaluate the operational intent for air traffic, space availability, and adverse conditions; and, if approved, facilitate information sharing with a network of other PSUs (FAA 2023). Additionally, the ability of AAM aircraft and PSUs to communicate with both commercial and general aviation aircraft (which have a range of sophisticated to basic avionics and communication capabilities, respectively) is also an unknown and unresolved risk. In the future, remotely piloted and automated aircraft could allow for increasingly complex and higher-volume



Source: FAA (2023).

Figure 6.1. FAA's envisioned airspace operating environment for AAM.

operations; however, the development of new regulations, policies, procedures, guidance materials, and training requirements is needed to enable these operations (Cohen et al. 2021). For these reasons, there are too many unknown factors to precisely estimate the likelihood and time horizon of air traffic management risks. Due to federal preemption in airspace management, MPOs and DOTs should monitor the growth and complexity of AAM operations and work with the FAA on strategies to mitigate airspace risks, as appropriate.

Source of Risk: Weather

Weather could pose several safety and operational risks for AAM. First, the sensitivity and safety risks of an aircraft and passengers to weather hazards increase with the decreasing size of aircraft (Reiche et al. 2021). Several weather conditions, such as low visibility, icing (snow/ice that accumulates on flight surfaces), wind shear, and precipitation (e.g., thunderstorms) could present a few weather-related risks for AAM. Table 6.2 describes some of the common atmospheric conditions that could affect AAM operations. Some of these weather conditions could pose greater risks to AAM due to low-altitude operations over urbanized areas, and an additional critical phase of flight (i.e., the transition from vertical to horizontal flight for VTOL operations). Strategies that are typically used in commercial aviation to overcome adverse weather conditions, such as delaying and rerouting flights to alternate airports are not particularly viable because the value proposition of AAM is premised on convenience and time savings over other transportation modes. Additionally, several proposed technologies for automated flight operations may be degraded in low-visibility conditions (i.e., LiDAR).

One exploratory study of AAM found that no more than 16% of aggregate operational time will be affected by weather. However, the study also notes that markets, such as New York City and London, could have greater weather constraints (Holden and Goel 2016). A key limitation of this study is that it focuses on case studies of markets rather than large multicity analyses. Another exploratory AAM climatology analysis, representing 10 U.S. cities with a variety of typologies and weather patterns, found the most favorable weather in the Pacific region of the United States (e.g., California and Hawaii), with much less favorable conditions along the northeastern seaboard (e.g., New York City) and Rocky Mountain regions (e.g., Denver) (Reiche et al. 2021). Average weather conditions were found to be less favorable for AAM in most seasons along the Eastern

Table 6.2. Common types of atmospheric conditions that may affect AAM.

Weather Condition	Description
High Winds	High winds and wind gusts can create several challenges for AAM operating in low-altitude and high-density built environments. High-rise buildings can also create canyon effects that produce unpredictable wind environments in urban centers.
Ice	Snow and ice can stick to critical surfaces (i.e., wings and rotors). Deicing systems and icephobic surfaces (currently under development by OEMs) may be able to help mitigate some of these risks.
Precipitation	Rain, thunderstorms, snow, sleet, and hail can create a variety of hazards for aircraft, which can include turbulence, tornadoes, icing, lightning, hail, heavy rain, downdrafts/microbursts, and other hazardous conditions.
Turbulence	Turbulence is an irregular motion of the air resulting from the air currents. Smaller aircraft are typically more susceptible to turbulence.
Visibility	Low visibility can limit a pilot's ability to safely fly, particularly during critical phases of flight such as takeoff and landing. For the vast majority of piloted aircraft under instrument flight rules conditions, pilots are still required to visually observe the landing environment. In the future, automated aircraft may be able to land in a greater variety of low-visibility conditions; however, weather minimums may still be required given potential technological limitations of the landing systems.
Wind Shear	The sudden change in wind speed or direction. Wind shear can be particularly hazardous during critical phases of flight.

Seaboard and the Southwest regions due to higher frequencies of nonvisual flight rules conditions, high winds, and vertical wind shear. The study also found that AAM could face critical weather challenges in the Rocky Mountain region due to lower temperatures, strong winds, and thunderstorms (Reiche et al. 2021). However, a key limitation of this study is the difficulty of precisely estimating the impacts of weather on AAM operations due to a variety of weather conditions and aircraft under development (each with different design characteristics and performance limitations). Additionally, the proprietary nature of these aircraft concepts results in limited publicly available information about their performance envelope (i.e., design capability in terms of airspeed, weight, cruise altitude, density altitude). While aircraft design and technology may be able to expand the performance limits, some weather challenges are likely to remain (Reiche et al. 2021). For these reasons, while there is a high likelihood of weather-related risks, it is difficult to estimate the precise likelihood and effects of weather due to the diversity of aircraft types and weather conditions.

The ability of AAM to scale operations may be highly dependent on the ability to provide dependable and consistent service with minimal delays. The integration of AAM into MOD and MaaS platforms could help improve traveler reliability and minimize delays by automatically routing a traveler's journey around travel disruptions, such as weather (Shaheen et al. 2020). This could include shifting trips from AAM to other modes at the onset of adverse weather. Additionally, AAM service providers and aircraft manufacturers may be able to consider mixed fleets of aircraft with different performance capabilities suited for a variety of weather conditions and climates. In conclusion, weather could present a variety of operational and safety risks to public agencies and be an important factor for why AAM may succeed in some markets and not others.

Source of Risk: Security

Ensuring personal, personnel, physical, and cybersecurity of all aspects of AAM will be critical to managing risk, maintaining safety, and building public confidence. A study by Shaheen et al. (2018b) conducted exploratory focus groups in Los Angeles and Washington, DC. In these focus groups, participants raised numerous concerns about the personal security of the passengers during booking, boarding, and onboard the aircraft from departure to arrival (Shaheen et al. 2018b). Key security concerns included hijacking; terrorism and aircraft sabotage; people pointing lasers at passengers and aircrew on takeoff and final approach; and unruly passengers and incidents involving passenger violence (particularly in an automated scenario without any aircrew on board). Data on security incidents involving general aviation (Part 91) and charter services (Part 135) are more limited than incidents involving commercial aviation (Part 121). Fortunately, the most serious incidents have declined in recent decades and remain relatively rare (in comparison to the total number of flights and flight hours). Since 2002, there have been 57 aircraft hijackings globally, and none in the United States since 9/11 (Mazareanu 2021). However, sabotage, terrorism, and other intentional acts are not always included in aviation safety statistics. For example, in 2020, the FAA reported 6,852 incidents involving lasers pointed at aircraft (known as "lasing") (FAA n.d.). As of September 2021, the FAA reported that incidents involving unruly passengers were occurring six times every 10,000 commercial aviation flights (FAA 2021a).

While terrorism, hijacking, aircraft sabotage, lasing, unruly passengers, and violence against passengers represent security risks, limited data and information on how AAM may operate make it difficult to ascertain a level of risk. For example, the risk of an AAM hijacking may be highly dependent on whether AAM passengers and personnel go through security screening, and if so, how extensive those screening procedures may be. There could also be scenarios where some AAM services or routes screen passengers and personnel while others do not (e.g., trips to or from an airport versus a route between two intracity nonairport locations).

Passenger background checks, no-fly lists for people convicted of certain criminal offenses, passenger rating systems (e.g., similar to the ratings provided by the drivers of TNCs to their riders), emergency dispatch buttons, and individual passenger compartments within an aircraft are strategies that could be employed to enhance personal safety. Additionally, technologies such as biometrics, passenger rating systems, and trusted traveler programs (like TSA's PreCheck, which offers expedited security screening for passengers who have completed a vetting process) are a few strategies that could be employed to enhance AAM security.

Regulators, air carriers, and ancillary service providers will likely need a system of policies and procedures to mitigate the risk of insiders (i.e., workers, contractors, vendors) from exploiting their legitimate access to AAM infrastructure and services for unauthorized purposes. Moreover, the physical security of vertiports, aircraft, charging/refueling, other physical infrastructure, and cargo will also need to be ensured. Finally, cybersecurity of all the enabling IT systems, including but not limited to ticketing/booking, air traffic management, communications, navigation, surveillance, and automated aircraft systems will be critical. Data collected by the European Air Traffic Management Computer Emergency Response Team (EATM-CERT) suggests that cybersecurity in aviation is becoming a growing risk (Bellamy 2021). EATM-CERT reported a 530% increase in aviation-related cyberattacks between 2019 and 2020, including 775 cyberattacks on airlines, 200 attacks on OEMs, and 150 attacks on airports. EATM-CERT reported that 95% (n = 739/775) of the cybersecurity incidents involving airlines were financially motivated (Bellamy 2021). In the future, close coordination among private-sector stakeholders, law enforcement, airports/vertiports, state DOTs, and national security agencies will be necessary to establish security standards and emergency plans for an array of scenarios.

Agency Goal: Sustainability and Environment

Source of Risk: Noise

Aircraft and helicopter noise are a frequently cited nuisance in neighborhoods around airports and heliports (FAA 2021b). In the near future, the high level of rotorcraft noise will likely limit the use of helicopters in urban areas (Shaheen et al. 2018b). Yedavalli and Mooberry (2019) conducted a general population survey across four locations: Los Angeles, Mexico City, Switzerland, and New Zealand. The study found that the second and third highest factors influencing the public perception of AAM were the type of sound generated by eVTOL aircraft and the volume of sound generated from an aircraft (Yedavalli and Mooberry 2019). An exploratory study by Shaheen et al. (2018b) included a combination of focus groups in Los Angeles and Washington, DC, and a general population survey in five U.S. cities. The study found that noise levels could erode support for AAM by the public (Shaheen et al. 2018b). Holden and Goel (2016) estimate that eVTOL aircraft should be one-half as loud as a medium-sized truck passing a house (75 to 80 decibels at 50 feet; approximately 62 decibels at 500 feet altitude)—approximately one-fourth as loud as the smallest four-seat helicopter on the market (Holden and Goel 2016). As the AAM market grows, noise concerns could be mitigated through technological improvements (i.e., aircraft design and electrification) or persist as the market matures into larger-scale operations (e.g., total ambient aircraft noise from multiple aircraft operating nearby). Increased demand for AAM poses a potentially greater risk that noise will be a concern for communities seeing more AAM. Additionally, as surface transportation electrifies, a potential reduction in overall ambient urban noise could make aircraft noise more perceptible in the future than it is today (Shaheen et al. 2018b).

It is difficult to estimate the precise likelihood or magnitude of noise risk because public tolerance of AAM noise may vary considerably based on factors such as aircraft and propulsion type; noise characteristics; time of day; take-off and landing procedures; and even use case.

Also, similar aircraft types and sizes may have very different sound profiles due to a variety of technical reasons. As such, policymakers should not assume that two different aircraft will sound alike. Additionally, the public may perceive noise from air ambulances as highly disruptive but be willing to accept the noise because the use case is less frequent and serves a public good.

In the future, the following AAM noise risks will need to be addressed:

- Volume of AAM noise (e.g., decibel level).
- Length of time AAM noise occurs.
- Time of day AAM noise occurs.
- Type or frequency of AAM noise.
- Number of people affected by AAM noise.
- Location of AAM noise and proximity to sensitive land uses.
- Number and location of takeoff and landing infrastructure.
- Comparison of AAM noise to other ambient noise.
- Differences between individual AAM aircraft noise compared to noise from scaled AAM operations.

Under existing law, local governments can plan and mitigate aviation noise primarily by promoting compatible land uses, requiring real estate disclosures, and including noise data in municipal codes. For larger aircraft (e.g., commercial aviation operations), the Airport Noise and Capacity Act (ANCA) of 1990 prohibits local governments from implementing aircraft noise restrictions after October 1990. Although airports can apply to the FAA to impose additional noise restrictions, such as curfews under FAR Part 161, as of April 2020, no airports have successfully received approval (Castagna 2020). In some cases, communities have closed smaller airports in response to community complaints about noise and quality of life (e.g., Santa Monica airport is now scheduled to close in 2028). While some airports have set recommended thresholds for community noise around airports, AAM may need to meet a stricter noise standard due to the nature of low-level flight over highly populated urban areas, coupled with scaled operations (e.g., high volume of AAM operations) (Holden and Goel 2016). At present, the primary mechanism for local, regional, and state agencies to influence noise may be through land use compatibility planning and the location and approval of takeoff and landing infrastructure such as vertiports and their siting relative to other types of land uses. In some cases, noise risk could be mitigated by not zoning or approving vertiports near sensitive land uses (or not allowing sensitive land uses near vertiports). Additionally, during the vertiport planning process, a public agency may approve a vertiport conditionally as long as the owner or operator prohibits flight operations during late night and early morning hours. Public agencies may own, operate, or fund vertiports to retain greater influence on AAM operations. In other cases, local agencies may be able to reduce the impacts of AAM noise through building codes, grants, and other practices, and require or incentivize the use of sound-deadening material in structures near vertiports and along key flight paths (Volpe Center 2017). Other noise mitigation measures may be more appropriate for the FAA and the private industry such as reducing noise through aircraft design. In the future, legislative and regulatory reform may expand policy mechanisms for noise abatement by local communities, MPOs, and state DOTs.

Source of Risk: Visual Pollution

Overcrowding of low-altitude aircraft in urbanized areas could create unwanted visual disturbances, particularly for nonessential use cases that can be completed using ground transportation options (Cohen and Shaheen 2022). However, the risks associated with visual pollution from AAM are difficult to ascertain because aesthetic impacts can vary based on several qualitative factors such as frequency of operations, location of operations relative to surrounding land uses, aircraft size, and other characteristics. For example, the public may be more annoyed by the presence of an air taxi flying over a historic neighborhood or green space than over the parking lot of a shopping mall. Similarly, the public may be more annoyed by multiple aircraft near one another (e.g., near a vertiport with a high volume of air traffic). The public could also be concerned by the size of an aircraft in the sky or by the color or materials (e.g., if the aircraft is reflective and causes a nuisance). For these reasons, the risks associated with visual pollution are diverse and difficult to quantify.

A few studies have attempted to understand the potential aesthetic impacts of UAM and UAS through user surveys; however, limited experience observing AAM in the built environment can make it difficult for survey respondents to accurately respond to these types of survey questions. Although studies on the impacts of AAM visual pollution on society are limited, some emerging literature on the impacts of visual pollution from UAS/drones as well as other sources may be able to provide some insight. A survey (n = 3,690) by the European Union Aviation Safety Agency on the potential societal barriers associated with AAM found that 19% and 16% of survey respondents raised concerns about visual pollution from drones and air taxis, respectively (European Union Aviation Safety Agency 2021). A survey (n = 1,465) on potential public concerns about the use of drones by the United States Postal Service found that approximately one in five respondents raised concerns about visual pollution associated with drone use. Interestingly, the findings were consistent among respondents in urban, suburban, and rural communities (United States Postal Service Office of the Inspector General 2016).

Several studies have also documented the impacts of commercial signage on historic neighborhoods (Abaya Gomez 2012; Chmielewski et al. 2016; Chmielewski et al. 2018; Jacksonville Community Council, Inc. 1985; Portella 2014; Wakil et al. 2021). These studies have proposed methodologies for assessing the impacts of advertising on visual pollution and tend to argue that initiatives to control visual pollution are necessary to maintain the historic character of city centers. Other studies have examined the impacts of wind turbines and cell phone towers on visual pollution (Nagle 2009; Jensen et al. 2014). One study on the impact of visual pollution of wind turbines on residential land values found that visual pollution reduces sales prices by up to approximately 3% (Jensen et al. 2014). Collectively, this aviation and nonaviation literature suggests that visual pollution could represent notable risks for public agencies; however, more research is needed.

AAM Risk Register by Risk Priority

The risk register of potential sources of risk from AAM is presented in a pair of tables: Tables 6.3a and 6.3b. Table 6.3a provides information typically found in a standard risk register (while applying the exceptions discussed in Chapter 2). This table presents its rows in descending order of assessed risk priority. Table 6.3b provides data that underly the calculation of both forms of the LOC measure, the SI-LOC and CB-LOC (see Chapter 2). These data are useful for raising awareness within the agency of the relevant aspects of a source of risk from emerging and disruptive technologies to agency goals. Therefore, each pair of tables provides more detail than is typical of standard risk registers to present the underlying methodology so that agencies can make modifications that will support their own deliberations and risk prioritization. The full methodology for doing so is found in Appendix C.

The same data appearing in Tables 3.2a, 4.1a, 5.1a, and 6.3a are presented in Appendix B sorted by agency goal.

Tables 6.3a and 6.3b are followed by a literature review on potential hazards (sources of risk) connected with AAM.

Table 6.3a. Risk register by risk priority for AAM technology group.

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
A1 Aircraft System Failure*	Critical aircraft system failure (e.g., degraded or loss of command and control or GPS, engine failure).	Incident reports and crashes with critical aircraft system failure as the proximate cause.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**4**	Require redundant systems as part of aircraft and airworthiness certification to minimize reliance on a single critical system that could cause catastrophic failure.	FAA.	**Extreme**
A2 Disparate Social and Environ-mental Impacts	Populations made vulnerable bear a dispropor-tionate burden of AAM impacts.	Demographics of people affected by AAM operations (e.g., flights and vertiports/takeoff and landing infrastructure).	3	Equity	Low-income households, minority communities, and other historically underserved populations bear disproportionate adverse effects of AAM operations (e.g., noise, visual pollution).	**4**	1. Leverage community engagement and engage communities and underrepresented populations early and often. 2. Incorporate environmental justice and disparate impact analysis as part of vertiport and airspace planning; consider conducting an analysis at regular intervals after implementing AAM service to determine whether changes are needed (e.g., routing). 3. Consider antidisplacement and gentrification policies in the vicinity of vertiports and intermodal passenger facilities with AAM.	U.S. DOT, FAA; state DOTs.	**Extreme**
A3 Aircraft Control Loss*	Loss of aircraft control (e.g., flight control system failure).	Incident reports and crashes with loss of aircraft control as the proximate cause.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**4**	1. Require redundant systems as part of aircraft and airworthiness certification to minimize reliance on a single critical system that could cause catastrophic failure. 2. Improve aircrew and ground crew training and certification to minimize the proximate cause(s) of loss of aircraft control (e.g., maintenance issue) and improve the likelihood of a safe recovery.	FAA.	**Extreme**

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Table 6.3a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	**Signpost Indicators to Watch**	**Likelihood Proxy**	**Goal Affected**	**Potential Consequences**	**Severity Score**	**Potential Mitigating Actions**	**Action Owners**	
A4 Software Failure*	Failure of autonomous and highly complex software.	Incident reports and crashes with software or computer systems failure as the proximate cause.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**3**	Work with industry and the FAA to identify potential flaws in flight and airspace management software and autonomous systems.	FAA.	**High**
A5 Flying Outside Approved Airspace	Flight outside approved airspace.	Incident reports and crashes involving AAM operations in prohibited airspace.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**3**	1. Establish pilot/remote operator communication and coordination with air traffic control, including compliance with all rules and regulations. 2. Improve airspace management processes and technologies, such as crew/air traffic control resource management, uncrewed traffic management (UTM), and providers of services of UAM (PSUs). 3. Work with DOD, DHS, and local law enforcement to strengthen enforcement mechanisms, such as aircraft interception, fines, and incarceration.	FAA.	**High**
A6 Unafford-ability of Services	AAM services are not mass-market affordable (passenger and aeromedical services).	Affordability of AAM services and use cases (e.g., per trip or mile metrics).	3	Equity	AAM services are only available to select users (e.g., business travelers).	**3**	1. Consider public policies that could enhance access or affordability to services (e.g., subsidies, essential air service programs). 2. Consider the regulation of areas such as fares, routes, and market entrants. 3. Consider taxing AAM to fund other types of mass-market transportation services (e.g., public transportation).	U.S. DOT, FAA, U.S. Congress.	**High**
A7 Privacy	Private data is shared in an unauthorized way or with an unauthorized recipient.	Sensitive data is shared, leaked, or hacked.	2	Security and Privacy	User, financial, location, trip, or other sensitive data is improperly handled, stored, shared, or hacked.	**3**	Implement data security standards and regulations governing handling and management of sensitive AAM data.	FAA, Federal Trade Commission, Federal Communi-cations Commission, state DOTs.	**Moderate-High**

A8 Privacy Concerns with Low-Altitude Flight	Residential communities concerned with low-altitude aircraft flying over homes and yards.	Privacy complaints from the community.	3	Equity	Privacy complaints along AAM routes, in the vicinity of vertiports, and around sensitive land uses.	**2**	Ban the use of various surveillance equipment, such as live-feed video cameras, infrared cameras, heat sensors, and radar on AAM aircraft.	FAA, state DOTs.	**Moderate-High**
A9 Unsafe Proximity to People and Property	Unsafe proximity of AAM operations to people or property.	Complaints from the public of incidents or crashes with injuries, loss of life, or loss of property due to AAM.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**2**	1. Improve airspace management processes and technologies, such as crew/air traffic control resource management, uncrewed traffic management (UTM), and providers of services of UAM (PSUs). 2. Work with DOD, DHS, and local law enforcement to strengthen enforcement mechanisms, such as aircraft interception, fines, and incarceration.	FAA.	**Moderate-High**
A10 Scaled Operational Noise	Scaled aircraft operations create a noise nuisance.	Noise complaints from the community.	2	Sustain-ability	Noise complaints along AAM routes, in the vicinity of vertiports, around sensitive land uses, or during certain times of day.	**3**	1. Establish or strengthen noise standards for AAM aircraft. 2. Permit restrictions on the hours of AAM operations for nonessential use cases over sensitive land uses.	FAA.	**Moderate-High**
A11 Terrorism	Ground and air incidents involving terrorism, sabotage, personnel or insider threats.	Incident reports involving terrorism, sabotage, personnel or insider threats.	2	Security and Privacy; Safety	Increase in the number of occurrences that affect or could affect AAM users, personnel, aircraft, or facilities.	**3**	1. Consider policies to help mitigate risks from terrorism, sabotage, and insider threats, such as personnel background checks. 2. Develop data sharing, security, and emergency response protocols for pre-, mid-, and post-flight.	TSA, law enforcement (local, state, and federal).	**Moderate-High**

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Table 6.3a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
A12 Visual Pollution	1. AAM creates unwanted visual disturbances, particularly for nonessential use cases that can be completed using ground. 2. Transportation options.	Aesthetic complaints from the community.	3	Equity	Aesthetic complaints along AAM routes, in the vicinity of vertiports, and around sensitive land uses.	**2**	Local governments implement design standards intended to conceal AAM from public view to the extent possible (e.g., setbacks, landscaping, form-based code, and design standards for vertiports).	Local government.	**Moderate-High**
A13 Ground Incidents	Ground incidents [e.g., foreign object debris (FOD), electrocution, vehicle crashes, falling objects, the risk of fires and explosions, conflicts between parked or taxiing aircraft and ground vehicles].	Incident reports and crashes involving ground personnel, vehicles, or parked and taxiing aircraft.	2	Safety	Increase in the number of occurrences that affect or could affect the safety of ground operations or result in a crash that causes death or serious injury, or in which the vehicle, aircraft, or ground facility receives substantial damage.	**2**	1. Conduct ground safety audits and implement policies and procedures to reduce the risk of personnel injuries and damage to aircraft, vehicles, and facilities. 2. Improve aircrew and ground crew training and certification to minimize the proximate cause(s) of ground safety incidents and the severity of incidents should they occur. 3. Improve/enhance first-response capabilities to ground safety incidents.	FAA, state DOTs, first responders/ emergency management agencies.	**Moderate**
A14 Over-whelming Air Traffic Control	Transition between controlled and uncontrolled airspace overwhelms air traffic control.	1. Reports from airspace users of midair collision close calls or other congestion issues. 2. Increase in-flight delays due to airspace congestion.	2	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**2**	Establish procedures for resolving collision avoidance alerts, particularly between AAM and commercial (Part 121) aircraft.	FAA.	**Moderate**

A15 Human Error	Human error as part of onboard or on-ground operations. The transition to full autonomy which may include operations centers with remote operators controlling multiple aircraft could create challenges associated with remote operator resource management (e.g., task saturation, miscommunication, and loss of situation awareness).	Incident reports and crashes with human error as the proximate cause.	1	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**3**	Work with industry and the FAA to enhance aircrew practices to reduce the likelihood and severity of human error.	FAA.	**Moderate**
A16 Passenger Incidents	Ground and air incidents involving unruly, unsafe, or disruptive passengers.	Incident reports involving unruly, unsafe, or disruptive passengers.	1	Security and Privacy; Safety	Increase in the number of occurrences that affect or could affect AAM users, personnel, aircraft, or facilities.	**3**	1. Consider policies to help mitigate risks from unruly/unsafe/disruptive passengers such as (a) passenger background checks; (b) no-fly lists for people convicted of certain criminal offenses; (c) passenger rating systems; (d) emergency dispatch buttons (to report unsafe or questionable behaviors). 2. Develop data sharing, security, and emergency response protocols for pre-, mid-, and post-flight.	TSA, law enforcement (local, state, and federal).	**Moderate**

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Table 6.3a. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
A17 Cybersecurity	Cybersecurity risks (e.g., hacking).	Incident reports and crashes with hacking as the proximate cause.	1	Security and Privacy; Safety	1. [Safety] Increase in the number of occurrences or severity of cyberattacks that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage. 2. [Security] Increase in the number of cyberattacks that affect or could affect AAM operations, reliability, or data security.	**3**	Work with industry, the Advanced Air Mobility Interagency Working Group, the FAA, CISA, and other federal agencies to develop AAM cybersecurity standards and detection systems to mitigate the likelihood and severity of a cyberattack, and quickly identify an attack should one occur.	FAA.	**Moderate**
A18 Congestion	Airspace congestion.	1. Reports from airspace users of midair collision close calls or other congestion issues. 2. Increase in-flight delays due to airspace congestion.	1	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	**2**	Improve airspace management processes and technologies, such as crew/air traffic control resource management, uncrewed traffic management (UTM), and providers of services of UAM (PSUs).	FAA.	**Low**
A19 Aircraft Noise	An aircraft creates a noise nuisance.	Noise complaints from the community.	1	Sustain-ability	Noise complaints along AAM routes, in the vicinity of vertiports, around sensitive land uses, or during certain times of day.	**2**	1. Establish or strengthen noise standards for AAM aircraft. 2. Permit restrictions on the hours of AAM operations for nonessential use cases over sensitive land uses.	FAA.	**Low**

*Note: The FAA's Aircraft Certification Service will require this likelihood to be extremely remote. These risks/hazards are already being considered as part of the type certification process. Type certification is the approval of the design of the aircraft and all components (including propellers, engines, control stations, etc.).
Source: RAND and Sam Schwartz.

Table 6.3b. Elements of two likelihood proxies and overall results for AAM technology group.

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Information	Response		Metric	Target	Tolerance Level (+/-)				
A1 Aircraft System Failure*	1	2	3	2	3	3	Incident reports and crashes with critical aircraft system failure as the proximate cause.	—	—	—	—	—	3
A2 Disparate Social and Environ-mental Impacts	3	2	3	3	4	3	Demographics of people affected by AAM operations (e.g., flights and vertiports/takeoff and landing infrastructure).	—	—	—	—	—	3
A3 Aircraft Control Loss*	1	2	3	2	3	3	Incident reports and crashes with loss of aircraft control as the proximate cause.	—	—	—	—	—	3
A4 Software Failure*	3	2	4	3	3	3	Incident reports and crashes with software or computer systems failure as the proximate cause.	—	—	—	—	—	3
A5 Flying Outside Approved Airspace	1	2	3	2	3	3	Incident reports and crashes involving AAM operations in prohibited airspace.	—	—	—	—	—	3
A6 Unafford-ability of Services	3	2	3	3	4	3	Affordability of AAM services and use cases (e.g., per trip or mile metrics).	—	—	—	—	—	3
A7 Privacy	2	2	4	2	2	2	Sensitive data is shared, leaked, or hacked.	—	—	—	—	—	2
A8 Privacy Concerns with Low-Altitude Flight	3	2	3	3	3	3	Privacy complaints from the community.	—	—	—	—	—	3
A9 Unsafe Proximity to People and Property	3	2	3	3	3	3	Complaints from the public of incidents or crashes with injuries, loss of life, or loss of property due to AAM.	—	—	—	—	—	3
A10 Scaled Operational Noise	2	2	3	2	2	2	Noise complaints from the community.	—	—	—	—	—	2

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Table 6.3b. (Continued).

Risk Source by Technology Group	Characteristics-Based Level of Concern (CB-LOC)					Concern Result	Signpost Indicator Level of Concern (SI-LOC)			State of Signpost Indicator	Signpost Indicator Trend	Signpost Result	Likelihood Proxy
	Novelty	Velocity	Size	Information	Response		Metric	Target	Tolerance Level (+/-)				
A11 Terrorism	2	2	4	3	2	2	Incident reports involving terrorism, sabotage personnel or insider threats.	—	—	—	—	—	2
A12 Visual Pollution	3	2	3	2	3	3	Aesthetic complaints from the community.	—	—	—	—	—	3
A13 Ground Incidents	3	2	3	3	2	2	Incident reports and crashes involving ground personnel, vehicles, or parked and taxiing aircraft.	—	—	—	—	—	2
A14 Over-whelming Air Traffic Control	2	2	2	2	2	2	1. Reports from airspace users of midair collision close calls or other congestion issues. 2. Increase in-flight delays due to airspace congestion.	—	—	—	—	—	2
A15 Human Error	2	1	2	2	2	1	Incident reports and crashes with human error as the proximate cause.	—	—	—	—	—	1
A16 Passenger Incidents	1	2	2	2	2	1	Incident reports involving unruly, unsafe, or disruptive passengers.	—	—	—	—	—	1
A17 Cyber-security	2	2	1	2	2	1	Incident reports and crashes with hacking as the proximate cause.	—	—	—	—	—	1
A18 Congestion	1	2	2	2	1	1	1. Reports from airspace users of midair collision close calls or other congestion issues. 2. Increase in-flight delays due to airspace congestion.	—	—	—	—	—	1
A19 Aircraft Noise	2	2	3	2	1	1	Noise complaints from the community.	—	—	—	—	—	1

*Note: The FAA's Aircraft Certification Service will require this likelihood to be extremely remote. These risks/hazards are already being considered as part of the type certification process. Type certification is the approval of the design of the aircraft and all components (including propellers, engines, control stations, etc.).
Source: RAND and Sam Schwartz.

CHAPTER 7

Policies and Strategies for Agency Resilience to Risks

A Dynamic Agency Posture Toward Risk

To better prepare for managing risk arising from emerging and disruptive technologies, agencies will need to work toward two goals. The first is to position themselves to be organizations that are resilient to the difficult-to-predict consequences emanating from the adoption of those technologies. This will require maintaining situational awareness and a capacity for foresight. The second will be to develop and implement courses of action designed to be robust to different potential futures arising from the consequences of technological innovations entering the transportation space. A robust course of action (policy, strategy, plan) is one that, by its design, can achieve its intended objectives across a range of possible future scenarios.

Chapters 3 through 6 presented the risk register resulting from the research. It is a snapshot taken at one point in time. For the risk register to be of the most value, agencies will need to make it a living tool by both updating it at regular intervals as the adoption of transportation innovation proceeds as well as adjusting it to reflect local circumstances and agency concerns and priorities. The risk register lists individual hazards, consequences, likelihood proxies, and mitigating actions by agencies. All the agency-specific mitigating actions presented in Chapters 3 through 6 were examined. From this analysis, a small set of higher-level policies or strategies were derived that appeared to be foundational to the most frequently cited mitigating actions. The set constitutes a basis for agencies to enhance their organizational resilience to change and impart greater robustness to strategies intended to achieve agency goals despite uncertainty over the direction of change.

Chapter 7 provides short versions of that small set of primers designed to highlight these higher-order directions that agencies could pursue to enhance the resilience of their risk management posture. Appendix D contains more detailed versions. Each could deservedly receive more extensive treatment with considerably greater detail. But the goal is not to be primers on agency process in general. Rather, the purpose of any of the strategy primers is chiefly to raise awareness of measures that could enhance the agency's ability to manage and mitigate risk. Taken together, they are intended to create an organizational consciousness of potential risk that connects risk management more directly with more routine operational and planning activities.

Some of the primers touch on topics to which agencies already devote much effort (e.g., Policy Primer 4: Ensure an Adaptive Culture of Safety; Policy Primer 8: Strengthen Sensitivity to Equity Implications of Agency Decisions). The purpose of including them in this set is threefold. The first purpose is to highlight each area as an aspect contributing to an overall posture of resilience to technology-related risk. The second purpose is to provide an opportunity to reconsider perspectives in the face of increasing risk from emerging and disruptive technologies. In the case of Policy Primer 4, for example, while agencies have personnel devoted to safety, perhaps the perspective of enterprise risk management and mitigation could lead to more extensive rethinking

Table 7.1. High-level policy primers and strategy briefs.

Policy Primer	Topic
1	Ensure Access to Necessary Workforce Skills
2	Monitor for Early Signpost Detection
3	Enhance Cybersecurity, Data Privacy, and Awareness
4	Ensure an Adaptive Culture of Safety to Risks from Emerging Technologies
5	Prepare for Data Sharing, Data Management, and Digital Policy
6	Detect and Examine Implicit Assumptions to Enhance Awareness
7	Create Capacity for Decision-Making under Deep Uncertainty (DMDU) (Nonpredictive) Analytics
8	Strengthen Sensitivity to Equity Implications of Agency Decisions
9	Practice Early Stakeholder and Community Engagement

consistent with bringing into being an organization-wide culture of safety. Another related consideration is to suggest that emerging technologies, while disruptive, may also convey opportunities to rethink broad agency goals such as safety. The third purpose is to put forward some specific recommendations either for new approaches and practices or to enhance awareness of individual, technology-generated hazards that deserve agency vigilance.

The primers included in this chapter and described extensively in Appendix D are shown in Table 7.1.

Because the briefs address different topics, the format for each brief may vary. Generally, each brief contains the following information:

1. Description of the higher-level policy or strategy.
2. Efficacy of the brief or strategy (i.e., how will this help?).
3. How to apply the policy or strategy, if applicable.
4. Stakeholder considerations.
5. Potential unintended consequences.
6. Hurdles or potential obstacles to the policy or strategy.
7. Notes, if any, on the timeframe for application and potential range or scope.

In some cases, the discussion will be grouped according to the specific technologies analyzed by the research team. In others, the discussion can be stated in more technology-agnostic terms. Where possible, references for further information as well as examples of agency use have been included.

Primers on Policies and Strategies

Policy Primer 1: Ensure Access to Necessary Workforce Skills

Description. Emerging technologies may demand a wide-ranging transition of the workforce both internally and externally. This includes creating or eliminating job functions and increasing or reducing the representation of specific skills.

How Will This Help? A trained and knowledgeable workforce is required to achieve both external and internal agency goals. State and local transportation agencies interact with a host of internal and external partners. Yet, skills that are common in private industry—such as data science, analytics, and business intelligence—may still be novel in agencies. By targeting human resource activities such as recruiting, training, retraining, succession management, and systematically identifying gaps in core competencies, transportation agencies can ensure that their workforce stays relevant—particularly for technological risks related to cybersecurity (Policy Primer 3) and safety (Policy Primer 4).

How to Apply in Practice. Begin by assessing current and emerging skills, identifying any resulting gaps, and creating a training and development plan. Retrain internal staff, hire outside experts, and create partnerships with external agents that can complement skills that agencies do not possess. There is a need for cybersecurity workforce preparedness across most emerging transportation technologies that, at a minimum, requires agencies to develop self-assessment capabilities and have systems, processes, and staff equipped with the skills necessary to detect, prevent, and mitigate cyber-related vulnerabilities.

Stakeholder Considerations. It is clear from both the scale and extent of potential workforce transition and dislocations that possible skill gaps are a consideration for more than just transport agencies. Stakeholder engagement, active partnership among government levels, and private-sector contact can help with determining internal agency requirements, and external requirements necessary to ensure safe and efficient operation, and balancing opportunity of access to evolving or newly emerging job descriptions.

Costs, Benefits, and Equity. Public agencies may lack the human or technical resources to accommodate and oversee emerging mode operations and initiatives (e.g., analyzing big data generated by mobility providers). The literature on U.S. skills highlights a consistent gap in access to opportunities. The ideal is for a motivated person with skills to achieve success. In practice, this might not be the reality. A transition plan could therefore identify, prioritize, and preemptively support (e.g., through retraining programs) workers at risk of falling behind while encouraging new entrants from traditionally underrepresented groups.

Potential Unintended Consequences. Outside of direct agency employment, over- or underestimation of labor force and skills is possible due to uncertain adoption rates and technological development. Even done right, the distribution of opportunities may not be equitable, leading to underemployment and wage stagnation in certain sectors.

Hurdles and Potential Obstacles. The risk of lacking access to necessary skills and workforce is compounded due to high rates of baby boomer retirement, changing needs of travelers and shippers, and new workforce methods, materials, and technologies. There is also an expanding array of emerging issues across environmental, administrative, and technical domains. Lack of information, uncertainties over technology implementation speed and scale, and an agency's internal capacity to plan and mitigate workforce-related risks are potential obstacles.

Owner(s). Transportation agency planners and their risk managers (both internal and external).

Range and Timeframe of Effectiveness. The purpose of this strategy primer is to raise awareness of measures that could enhance the agency's ability to manage and mitigate risk related to workforce obsolescence. Considering workforce-related threats in the future, a just transition plan could be implemented as soon as planners identify skills and opportunity gaps through internal gap analysis exercises.

Policy Primer 2: Monitor for Early Signpost Detection

An organizational awareness of early indicators of emerging risks would connect risk management directly with more routine operational and planning activities.

Description. Signposts are early indicators or warnings of a potential hazard. They are signals of how the future may be trending and so affect the plausibility of different scenarios for the future. As such, they should help agencies as part of a risk management strategy for emerging and disruptive technologies.

How Will This Help? The strategy of thinking in terms of signposts is not limited to being associated with any one risk register row. The concept is a useful habit to inculcate into agency processes and deliberations. Signpost indicators may usefully be allied to the process of making assumptions explicit, as discussed in Policy Primer 6.

How to Apply in Practice. It will serve agencies best to first consider how a risk register row could affect the agency's ability to meet its goals: "What would be the best early warning sign of an emerging risk?" Then, assess what data are available, where gaps exist, and how the appropriate signpost can be framed for future tracking as the technology's implementation goes forward.

Proper framing of a signpost indicator must delineate a baseline target level as the reference for trends as well as tolerance levels above and below these targets. Periodic assessments of the signpost indicator would be advisable to ensure the chosen metric continues to be an effective indicator. Agencies should add or subtract from the suggested list of signposts in the risk register based on local conditions.

Stakeholder Considerations. Engagement with community members will help guide the selection of early warning signposts of risk to agency goals and community interests. This can help agencies achieve community-facing goals as well as develop a robust understanding of the challenges facing their region and the hazards their community may be most sensitive to.

Costs, Benefits, and Equity. An agency may be faced with larger issues later in the timeline of a technology's implementation if it does not have in place a capacity to monitor early warning signposts and so better respond to potential threats which might compromise an agency's ability to fulfill its goals. Benefits of monitoring include early awareness of and potential for timely response to indications of unmet agency goals, especially those of equity and responsiveness to historically underserved communities.

Potential Unintended Consequences. Any single indicator is susceptible to either false positives or false negatives. Some issues may be reduced by working with a dashboard of several indicators. But this increases costs and the more signposts, the less value in any one such indicator. The best guard against false readings would be to periodically review the value of the information received.

Two approaches could reduce some of the institutional or cognitive biases that might come into play. One is to broaden the diversity of representation in the process of developing signposts. This could include other agencies, experts, and potentially affected communities. The other would be broadening the task of monitoring beyond the risk management team to agency units associated with a particular hazard.

Hurdles and Potential Obstacles. Data collection will lag behind technology deployment. Transportation agencies may lack the skillsets needed to analyze the data emerging mobility technologies are likely to produce. As knowledge of emerging mobility technologies evolves, so can their signposts. Recurring discussions to determine what risks and their associated hazards are most important to an agency and region should take place.

Owner(s). Transportation agency planners and their risk managers.

Range and Timeframe of Effectiveness. Signposts may be established as soon as planners have identified a potential hazard/source of risk that may emerge from an implemented or prospective technology. Gap analysis comparing the identified signpost indicator to available data sources could affect both signpost choice and future monitoring. Collection and analysis of selected signpost data may only be available once diffusion of the technology is underway.

Policy Primer 3: Enhance Cybersecurity, Data Privacy, and Awareness

Agencies need to raise their awareness of measures that could enhance the ability to manage and mitigate risk related to cybersecurity and privacy.

Description. Emerging and disruptive technologies by their very nature may blur the lines of categorical risk. The expected connected nature of new transportation modes envisions vehicles interacting with other vehicles, personal mobile devices, transportation infrastructure, and communications and payment networks creating avenues of attack in the physical and information space.

How Will This Help? Enhancing information security and implementing mitigation strategies when security cannot be guaranteed will enhance the protection of data and privacy as well as the security of new mobility technologies and infrastructure against various forms of denial of use or other types of attacks with mass effects.

How to Apply in Practice. There are three cybersecurity objectives to meet in a cyber-physical system to prevent or mitigate risks: (1) reliable service and availability, (2) integrity of the data and data exchange, and (3) confidentiality of the data transmissions (Gottumukkala et al. 2019). The following strategies can aid practitioners: strict data access standards, detection algorithms, cybersecurity testing, raising cybersecurity awareness, and creating clear terms of use agreements.

Stakeholder Considerations. Sources of risk, consequences, and solutions extend beyond the purview of government organizations; dialogue with other stakeholders will be key to remaining on the cutting edge of cybersecurity. For example, private industry will need to continually update agencies on best practices for data interoperability standards, cloud storage of user information, and protocols for data access.

Costs, Benefits, and Equity. Data privacy, thefts, and breaches should be thought of as potential costs to all if actions are not taken to develop mitigation strategies early on.

Potential Unintended Consequences. Inadequate data sharing and collaboration may result in information asymmetry; without ample data and information sharing, mobility services may have more information on travel patterns than DOTs and transit agencies. This could lead to loss of effectiveness by agencies in operations, planning, and regulation. If incorrectly controlled and stored, data points can be combined to form PII from some more innocuous-seeming data sources (National Association of City Transportation Officials 2019, 76).

Hurdles and Potential Obstacles. Protocols, standards, and best practices for ensuring cybersecurity are still being developed. There are also limited services available to perform cybersecurity-related testing and assessment. DOTs and MPOs will need to collaborate with the federal government, vendors, and other stakeholders to see passage of comprehensive legislation to strengthen cybersecurity standards, hold manufacturers accountable for breaches, but also to determine their roles in the ecosystem providing cybersecurity and personal privacy (National Association of City Transportation Officials 2019, 37).

Owner(s). State DOTs, MPOs, private-sector vendors and service providers, and various agencies of the federal government beyond the U.S. DOT.

Range and Timeframe of Effectiveness. There will be a need for cybersecurity and regulation to combat nefarious actors throughout the growth and adoption of emerging transportation technologies. Further, with each new technology development come new opportunities for system failure, resulting in a need for early and continuous attention.

Policy Primer 4: Ensure an Adaptive Culture of Safety to Risks from Emerging Technologies

An adaptive safe system approach and culture will ensure organizations employ a proactive posture toward addressing new or changing hazards introduced by emerging technology.

Description. An adaptive culture of safety effectively adjusts and evolves in response to changing circumstances and challenges. Safety is not a static goal but a continuous process of improvement that requires ongoing evaluation and adaptation to new risk sources. The ability of the Safe System Approach to expand, adapt, and develop beyond its original envisioned scope is a key component of a resilient system.

How Will This Help? By increasing awareness of and prioritizing a dynamic safe system approach, transport agencies can focus on designing infrastructure solutions less vulnerable to human error and sufficiently flexible to respond in an uncertain future and provide a safer and more secure mobility ecosystem for all.

How to Apply in Practice. The first step is to integrate the Safe System Approach (Vision Zero framework) into infrastructure planning and design of transportation systems. Next, the current Safe System Approach should be upgraded with proactive tools to continually identify and account for novel safety issues being introduced to the system by emerging and disruptive technologies. As these technologies mature, agencies and key stakeholders may need to expand the elements that define a Safe System Approach to develop resiliency. Some potential policies in practice include developing proactive early notification systems, updating existing standards and guides, creating new standards that require additional safety features, performing workforce (re)training, integrating real-time mapping into planning decisions, and sharing best practices and lessons learned.

Stakeholder Considerations. Good communication between MPOs, DOTs, industry partners, and third parties responsible for emerging technologies will help highlight key safety concerns and solutions earlier in adoption phases. MPOs and DOTs will need to develop plans with educational institutions to prepare a workforce for evolving needs in addressing all aspects of safety. Also, MPOs and DOTs may need to liaise with service providers and contract workers especially when employee efforts can influence the safe operation of the platform itself.

Costs, Benefits, and Equity. Infrastructural change toward the Vision Zero goal can require large investments. However, developing such solutions that are multiuse, flexible, and modular may allow regions to transform how emerging technologies might assist agencies to respond with a safe system approach. Restructuring property and fuel taxes should be considered so that regions can continue investing in Vision Zero infrastructure. In terms of ethical and equity considerations, certain hiring practices present the risk of worker exploitation and worker safety.

Potential Unintended Consequences. Adaptive infrastructure solutions may allow regions to be resilient, but may also lead to an increase in expenditure. Hasty authorization for technology operations absent objective and verifiable safety performance standards and tests may result in new risks and hazards.

Hurdles and Potential Obstacles. Creating requirements for data sharing will likely be the first obstacle to overcome to identify where safety-based policy improvements are needed. There may also be challenges in predicting and planning safety needs and infrastructure investment, matching development timelines with adoption rates, and staying within regional transportation budgets and capacities. Another challenge is public perception such that, even if decision-makers take a safety-first approach, hesitation and concerns over personal safety may be a barrier to individual user adoption of safety tools and practices.

Owner(s). MPO and DOT leadership and long-range transportation planners/modelers.

Range and Timeframe of Effectiveness. Taking a safety-first approach in transportation planning should happen as early as possible. Even if adoption timelines are 10 to 20 years, it is not too early to begin working toward Vision Zero goals.

Policy Primer 5: Prepare for Data Sharing, Data Management, and Digital Policy

This strategy primer raises awareness of measures that could enhance safe data sharing and data management necessary with the increasing adoption of emerging and disruptive mobility technologies.

Description. The sharing of data among service providers, public agencies, and other key public- and private-sector stakeholders can increase understanding of the consequences of innovative emerging transportation technologies for travel behavior, equity, and the environment. However, with uncertain standards for data sharing and management, the exchange of data can be onerous and present several security and privacy risks. The primer is intended to create an organizational consciousness of the potential risk of insufficient attention to data-sharing issues.

How Will This Help? The successful sharing and management of data generated by emerging transportation technologies has the potential to enable public agencies at all levels of government to operationalize digital infrastructure and leverage it dynamically to manage mobility policy and public rights-of-way such as curb space and potentially airspace management.

How to Apply in Practice. Public agencies should consider developing guiding principles for data sharing and management such as

- Establish standards for collecting and publishing data that are consistent with industry standards and other public entity standards, and that address interoperability issues. Standards could also be developed to aggregate and disseminate data in real time.
- Create data management policies such as establishing user agreements for those sharing and receiving data. These user agreements can also include conditions for data use such as requiring mobility service providers to grant an open license to ensure that aggregated and anonymized data are available to the public and that prohibited data uses are articulated.
- Develop data accessibility standards to ensure that data made available to public agencies are in an open format that can be downloaded, indexed, searchable, and machine-readable to allow automated processing.

Stakeholder Considerations. Public agencies may lack staff capability to handle the safe sharing and storage of data generated by emerging transportation technologies. Public agencies may consider developing new positions (e.g., chief technology officer) to maintain in-house capabilities and coordinating across organizations to establish standard practices for data sharing and management.

Potential Unintended Consequences. Emerging mobility technologies have the potential to generate vast amounts of data; how this data is stored, shared, and managed can raise several concerns. These concerns include the following:

- Compromised Traveler Privacy. Mobility services or apps may intentionally or unintentionally collect sensitive and PII.
- Trade Secrets Disclosure. Mobility services or apps may generate or rely on proprietary information that can be important to an organization's unique business plan or growth strategy.
- Revelation through Public Records Laws. Data used by public agencies may be subject to public records requests which can potentially reveal traveler or proprietary information.
- Data Security. Data shared between agencies and organizations may present security risks (e.g., security breaches, data theft).
- Lack of Universal Standards. Data may be generated in a nonuniform way which can complicate data sharing.

Hurdles and Potential Obstacles. Despite the value of sharing data, there can be concerns about what data are shared, how the data are shared, who sees the data, and what the data are used for. Data sharing may pose challenges regarding traveler privacy, protecting trade secrets, public records requirements, data security, institutional capacity, and the lack of universal data management standards.

Policy Primer 6: Detect and Examine Implicit Assumptions to Enhance Awareness

An agency's ability to recognize important underlying assumptions that should be made explicit will help to better manage and mitigate risk stemming from adoption of emerging and disruptive mobility technologies.

Description. All plans are forced to make assumptions about the future. Some are explicitly identified. Implicit or unconsidered assumptions can be a source of significant risk management strategy failure. A resilient risk posture includes insight into where hidden assumptions and key assumptions may lie.

How Will This Help? Static risk management approaches can provide a baseline but also can lead to misplaced concreteness. Agencies will be well served to establish a posture of resilience toward this category of risk by inculcating a planning culture of thinking in terms of alternative assumptions. Weighing assumptions allows agencies to frame robust risk management postures and opens the possibility for hedging against possible broken assumptions or shaping the unfolding implementation of new technologies.

How to Apply in Practice. Assumption-based planning (ABP) is focused on the discovery and characterization of explicit and implicit assumptions (Dewar 2002). It is intended as a tool for reducing avoidable surprises that could disrupt plans. Several methods are available for identifying load-bearing assumptions, which are vulnerable to challenging future scenarios. They serve as entrees to a whole-of-agency approach to detecting assumptions, determining the degree of their load-bearing relevance to the agency's goals, and considering potential consequences for agency goals.

Stakeholder Considerations. Detecting and evaluating assumptions involves internal activities as well as outreach to other government bodies, communities, and stakeholder groups.

In addition to planning products, the process outcomes may prove equally valuable for connections made and channels of communication opened through stakeholder involvement.

Costs, Benefits, and Equity. The issue of equity may be one of the most telling applications of assumption detection to enhance agency approaches to risk. Planning employs aggregates and averages that can mask effects that fall most heavily on lower socioeconomic deciles. Comparing initial states with later-stage or final states does not address the question of how the time path may affect different groups along the way. The issue of equity can become the occasion for explicit discussion of assumptions.

Potential Unintended Consequences. There is always the danger of greater concreteness being misunderstood as a guarantee against surprise. It would be good practice to review the premises of earlier assessments on an annual basis. New information becoming available or different personnel becoming involved in planning and operations are occasions for considering possible changes in underlying assumptions.

Hurdles and Potential Obstacles. There may be resistance to incorporating new approaches in existing processes for risk management planning. This would certainly be the case for those activities that are most central to the planning functions of the agency and the modeling and analyses that support them. However, if approached carefully, by assessing assumptions, risk management may well be seen as coming more into the main line of agency focus and enhancing agency goals. Employing new techniques in risk management and using new methods to enhance the means for agency personnel to perceive potential sources of risk early on are likely to be welcomed.

Owner(s). Transportation agency risk managers and planners.

Range and Timeframe of Effectiveness. Determining and analyzing underlying assumptions will be valuable when agencies engage in processes related to risk management. Further, this approach will be useful in gaining greater awareness of the equity implications of measures that may have been decided on based on the presumed benefits to the widest segment of the population or utilizers of transportation modes. It would be valuable to review assumptions on an annual basis or when new information becomes available, or the agency risk managers can engage additional expertise and community input.

Policy Primer 7: Create Capacity for Decision-Making under Deep Uncertainty (DMDU) (Nonpredictive) Analytics

Means exist to enhance an agency's ability to model, analyze, and plan more effectively despite an increase in transportation system uncertainties. These can allow agencies to explore alternative strategies and policies that are robust (i.e., meet preset criteria for good outcomes) across a range of possible future scenarios.

Description. Transportation agencies produce planning documents using methods based on prediction, but forecasts have become increasingly unreliable due to increased uncertainty in transportation systems and those that surround them. DMDU methods are being adopted by agencies to enhance strategic-level transportation planning.

How Will This Help? DMDU methods instead characterize uncertainties in terms of the specific problem: "Which assumptions do I need to believe to recommend one course of short-term actions over another?" DMDU is also designed to support a participatory process of "deliberation with analysis," which can help implement stakeholder engagement. Traditional planning methods can foster overconfidence, limit consideration of alternatives, or lead to gridlock when stakeholders question assumptions.

DMDU methods are varied in their format and consist of both qualitative and quantitative model-based approaches. In general, they are designed to examine the implications of different assumptions about the future. Quantitative methods, such as robust decision-making (RDM) may generate hundreds or hundreds of thousands of simulations that, in turn, provide a database for systematic examination of consequences. Analytical tools in agencies such as transportation demand models, however, very often take several days of calculation to perform a single run. It may well be that some adoption of DMDU methods could allow planners and those charged with agency risk management to have means for bringing more analytical support to their efforts.

How to Apply in Practice. Initial uses in transportation are not to supplant large travel demand models. Rather, DMDU tools have been used to shed greater light and support a strategic perspective within the agency. Applications begin with proposing an agency plan, stress testing the plan over plausible futures, generating policy-relevant scenarios, and determining robust and flexible strategies that perform well over different futures.

ABP, a nonquantitative method, would illuminate how best to establish signpost indicators along with their targets and tolerances to create the SI-LOC likelihood proxy. RDM uses models and simulations to discover scenarios that might threaten the success of agency plans and around which signpost indicators could be framed. Several software packages are available to support agencies using model-based DMDU, including Travel Mode Improvement Program-Exploratory Modeling and Analysis Tool (TMIP-EMAT) and VisionEval, both of which have been supported by FHWA.

Appendix D provides a more detailed discussion of specific qualitative and quantitative methods.

Stakeholder Considerations. Moving away from prediction may help agencies discover and test strategies having low regret, that flexibly evolve with new information, and identify hedging and shaping actions in a way that broadens engagement by asking, "What will happen in the future?" but rather, "What might happen by varying model assumptions?"

Hurdles and Potential Obstacles. The largest issues will be internal with a need to gain buy-in, recognize turf issues, and conceptualize work processes. Consider early joint exposure to DMDU methods and tools between agency planning and government regulatory agency staff to expand awareness of what might be possible and the potential utility of output provided by DMDU methods and analyses.

Owner(s). Transportation agency risk managers and planners.

Range and Timeframe of Effectiveness. This effort would reward early preparation, particularly for the introduction of new methodologies that will likely have the greatest effect once in place and accepted as a regular process within the agency organization.

Policy Primer 8: Strengthen Sensitivity to Equity Implications of Agency Decisions

Description. Past transportation decisions have led to inequitable sharing of benefits and burdens across different communities even if unintentionally. There is a need to pay attention to communities that have been made vulnerable to ensure that historical burdens are neither perpetuated nor new ones introduced through the implementation of emerging and disruptive technologies.

How Will This Help? Agencies will need frameworks, postures, and approaches for building equity into every step of the decision-making process so that all emerging mobility technologies will have equity considerations integrated into each step of the decision-making process.

How to Apply in Practice. The first step is to identify equity as a primary agency goal. To assess previous structural inequities within an agency and achieve equitable policy outcomes in the future, agencies require the ability to assess equity concerns using data, a commitment to distribute resources equitably, and the means to assess equity using a multiattribute framework naming specific goals.

There are several approaches for assessing equity, for example: (1) procedural equity; (2) distributional equity; (3) structural equity (McDermott et al. 2013). Procedural equity requires prioritizing knowledge sharing and information gathering from individuals who represent the full diversity of the community. By acknowledging power imbalances that are inherent to many governmental agencies, agencies can work toward a more equitable approach to information gathering by, for example, building channels for collecting information from community members' lived experiences. Strong procedural equity is a prerequisite for distributional equity—distribution of resources, services, and socioeconomic and environmental costs and benefits, prioritizing first the communities that have been affected most by previous burdens. Finally, structural equity addresses the larger systematic structures that produce disparate outcomes for community groups. Applying these three approaches requires new tools, strategies, and a culture shift that can radically transform deeply rooted practices to ensure fairness in policymaking and planning processes.

Stakeholder Considerations. Partnerships between providers and community-based organizations can adapt emerging mobility technologies to local community needs. Agencies can also work with educational institutions to develop a workforce training program to create a jobs pipeline in emerging mobility technologies.

As these emerging mobility technologies become ever-present, decision-makers will need to assess how to reduce barriers to utilization for low-income individuals and individuals without access to or the ability to use a smartphone. Improving Internet accessibility, developing systems to improve user safety, developing context-sensitive transportation solutions, and prioritizing data collection on equity measures are necessary to create equitable outcomes.

Potential Unintended Consequences. Emerging mobility technologies have the potential for introducing systems that are unaffordable for large portions of the population, thus affecting goals of mobility. Emerging mobility technologies also have the potential to displace those who make a living in current systems. New technology and infrastructure to support these modes should reach across communities with special regard for those communities that have been made more vulnerable (e.g., public EV charging facilities are more necessary for those without the ability to charge their vehicles at home). Governments will need to emplace mechanisms to protect communities from threats of displacement, consequences for viable economic activity, and environmental hazards.

Hurdles and Potential Obstacles. Data acquisition will be challenging. Inequitable access to services is likely to occur unless special measures are put into place. There are also likely to be challenges due to availability of personal smartphones or digital payment systems. Policies that allow MOD/MaaS drivers to preview trip origins or destinations may also lead drivers to be more selective about the communities they serve.

Policy Primer 9: Practice Early Stakeholder and Community Engagement

The primer is intended to raise awareness of measures that could enhance agency ability to manage and mitigate risk through stakeholder and community engagement.

Description. Community and stakeholder engagement can ensure that everyone has the opportunity to participate in the decisions about emerging transportation technologies that affect them.

How Will This Help? Collaborating with stakeholders and community groups to create a shared vision for emerging transportation technologies is critical for risk management. In addition to cross-agency communication and collaboration, there are many reasons for agencies to engage stakeholders and the public. For many years, state and federal laws have required public hearings to precede official decisions. While environmental processes may be an effective tool for assessing the technical viability of innovative mobility deployments, early, deep stakeholder and community engagement is important to understand and address potential concerns.

How to Apply in Practice. Common engagement methods include town halls, public hearings, open houses, focus groups, small group discussions, workshops, and peer exchanges. Engagement practices will often vary based on an agency's policies, procedures, and local customs. Some municipalities have provided municipal staff and regulatory agencies wider authority to develop and manage processes (e.g., public comment periods and administrative law hearings). Collaborative public processes often reflect best practices in policymaking and planning because they can reduce conflict (and litigation) among stakeholders while advancing shared goals.

Stakeholder Considerations. It is important to distinguish between stakeholder and community engagement. Community engagement is a process that involves the public in the transportation decision-making process. It provides the public with the information they need to be involved in a meaningful way and communicates to the public how their input influences the decision. Stakeholder engagement is more targeted and involves those who are affected by an action in the decision-making process.

Potential Unintended Consequences. There are several risks with stakeholder and community engagement. Examples of potential challenges include the following:

- Disrespectful, malicious, inflammatory, obscene, intolerant, inappropriate, or illegal conversations.
- Public criticism of the process, proposal, or participants in the process.
- Using stakeholder and community engagement for political ends.
- Unrealistic expectations (this can be from the public or the agency leadership).
- Undue influence leading to greater bias/predetermined outcomes.
- Community confusion about a project, policy, or proposal.
- Overzealous participation (e.g., some participants speak louder than others making it difficult for everyone to have a voice).
- Development of strategies that are difficult to scale.

Hurdles and Potential Obstacles. Some potential stakeholder and community engagement hurdles can include engagement fatigue; distrust of the public agency or government; challenges with being comfortable in public speaking or engaging in some types of settings; lack of participation by stakeholders or the public in the process; language barriers; health and safety considerations (e.g., pandemic); and digital divide/computer literacy (e.g., unable to participate in engagement methods). Engaging the public and stakeholders openly, honestly, and without predetermined outcomes can help mitigate many of these challenges. Additionally, providing opportunities to engage in multiple ways, both physically and virtually, can help expand the accessibility of community and stakeholder engagement.

CHAPTER 8

Moving Forward Inside State DOTs and MPOs

Innovative technologies in transportation systems provide new means to achieve core goals. They could enhance mobility and access, create safer travel, provide more efficient and smarter solutions to address transportation demand and reach more people with the potential for greater equity. Nevertheless, novel technology often is accompanied by unintended consequences that, if not analyzed and managed, pose a risk to state DOTs' and MPOs' goals. This report provides a framework to support agencies in managing the associated risks and creating readiness for current and future technological innovations.

Transportation agencies need to manage sources of risk from emerging and disruptive technologies and the challenges that accompany them. Modal forms and their distribution are changing from ICE-powered vehicles to EVs of various types, from private ownership to shared vehicles, from current transit options to the prospect of roads filled with CAVs and on through AAM technologies that will leave the roads entirely. Transformations in society, economy, and other underlying systems are also changing rapidly. Agencies will be hard-pressed to be sufficiently foresightful to anticipate all the changes and sources of risk to come. Yet, they will need to become adept in operating under future circumstances to be successful. Change will not come as a succession of technological plateaus with each in turn affording the time necessary to learn the new rules of thumb before the next wave of change. Rather, the dynamics of change will be continuous.

Among the most fruitful activities for this project were the peer exchanges held with transportation agency professionals, technology experts, and members of stakeholder communities (Chapter 1 and Appendix C). There was general recognition in these meetings of the profound changes already occurring and the promise of more to come. The prospects for transportation are exciting but also unsettling for transportation agency planning and operations. Participants saw many needs for fundamental change in transportation agency concepts, approaches, and activities if they are to continue to meet the range of public goals.

A risk register is an effective tool for categorizing and prioritizing sources of risk and their possible consequences and cataloging alternative means for reducing vulnerabilities and exposures or mitigating consequences. Uncertainty is not a failure of due diligence; it is an inherent aspect of the technology innovation and adoption enterprise. AAM may be on the horizon, but it is hard to determine when and to what extent they will be deployed, the types of aircraft that will be deployed, and the use cases AAM will serve. There is risk in cataloging risk when trends are still fluid; naming sources of risk can easily be conflated with retaining a considerable level of control. Such a catalog could reinforce an agency attitude toward risk that is ill-suited to the constantly transforming dynamics. This could lead to an illusory and perhaps even unconscious tendency to fit today's needs into the forms of the past and make agencies less wary of surprise and less resilient to change.

The research attempts to take the familiar forms of the risk register and risk matrix and transform them into a tool that responds to change and subsequent updates of information so that agencies can fulfill specific objectives in the presence of accelerating disruptive technology and the transformation of modal forms and shares. The report intends to convey that the lodestone for agencies must be to achieve a risk management posture that will allow them to be both foresightful and resilient. The intention was to go beyond providing a snapshot compendium to providing agency risk managers with tools for achieving that organizational resilience and building into their plans greater robustness to the different paths the future might take.

Appendix C provides a fundamental discussion of the nature and sources of risk, its decomposition into hazards, likelihoods, exposure, vulnerability, and consequences. It discusses how risk management is complicated by uncertainty and the presence of competing assumptions. It then presents methodological solutions emerging from this project's research for how to encompass the dynamics of change, the varying circumstances of the many different locations in which agencies operate, and the different potential embodiments of emerging mobility technologies within the framework of the traditional risk register. These solutions transform the risk register into something better suited to the risk management problem agencies increasingly face. The method outlined in that discussion provides the occasion and the framework for agencies to address the problem of risk in a manner that accounts for their local situation and supports an organization-wide approach to risk management.

Chapters 3 through 6 present the risk register from this research effort. The register is a snapshot of current understanding and a template on which to build. It contains fundamental differences from a traditional risk register. This register is intended to be tailored to individual agency needs and be capable of reflecting changes in information.

The risk register presented in these chapters should be read as part of an overall posture for risk management that includes the concepts offered in Chapter 7. That chapter's high-level policy primers are aimed at presenting broader, high-level risk mitigation strategies and policies sufficient for implementation in a technology-agnostic manner across agency goals. The policy primers constitute actionable avenues for enhancing agency agility. They contain key elements of effective mitigation of particular sources of risk to achieve a resilient organization—one that takes a comprehensive approach to risk management rather than compartmentalize it within a few select offices and among a dedicated staff.

The methods discussed are intended to support agency risk management when long-held rules of thumb no longer appear to apply and the new ones remain far from clear. The research team drew on the experience of novel analytical decision-support methods being applied in transportation but also on the application of leading-edge tools for decision-making under uncertainty being applied in nontransportation agencies involved in other aspects of public policy such as water or energy planning.

The sum of the components is intended to provide value to DOTs and MPOs through a new framework to strengthen agency resilience to emerging technologies. While there are volumes written on new mobility, many cited in this report, the combination of these components offers a holistic approach for agencies to proactively manage existing and new emerging technologies. All may contribute to a resilient posture toward the management of emerging risk.

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Acronyms and Abbreviations

AAM	advanced air mobility
ABP	assumption-based planning
ANCA	Airport Noise and Capacity Act
API	application programming interface
AV	autonomous vehicle
BEV	battery electric vehicle
BIL	Bipartisan Infrastructure Law
BMS	battery management system
CARB	California Air Resources Board
CAV	connected autonomous vehicle
CB-LOC	characteristics-based level of concern
CEQA	California Environmental Quality Act
CISA	Cybersecurity and Infrastructure Security Agency
COVID-19	coronavirus disease 2019
CV	connected vehicle
DAC	disadvantaged communities
DCFC	direct current fast charging
DOT	department of transportation
DSRC	direct short-range communications
EATM-CERT	European Air Traffic Management Computer Emergency Response Team
EU	European Union
EV	electric vehicle
EVSE	electric vehicle supply equipment
FDIA	false data injection attack
FHV	for-hire vehicle
FOD	foreign object debris
GBFS	General Bikeshare Feed Specification
GBNRTC	Greater Buffalo Niagara Regional Transportation Council
GDPR	General Data Protection Regulation
GHG	greenhouse gas
GTFS	general transit feed specification
HD	heavy duty
HEV	hybrid electric vehicle
HTF	Highway Trust Fund
ICE	internal combustion engine
IIJA	Infrastructure Investment and Jobs Act
IP	Internet protocol

ITC	income tax credit
LCV	light commercial vehicle
LiDAR	Light Detection and Ranging
LOC	level of concern
LSAV	low-speed automated vehicle
MaaS	mobility as a service
MAPC	Massachusetts Metropolitan Area Planning Council
MD	medium duty
MDS	mobility data specification
MFT	motor fuel excise tax
MITM	man-in-the-middle
MOD	mobility on demand
MPO	metropolitan planning organization
MTA	Metropolitan Transportation Authority
NEPA	National Environmental Policy Act
NEVI	National Electric Vehicle Infrastructure
NIST	National Institute for Standards and Technology
NYSDOT	New York State Department of Transportation
ODD	operational design domain
ODOT	Oregon Department of Transportation
OEM	original equipment manufacturer
OMF	Open Mobility Foundation
OSHA	Occupational Safety and Health Administration
PBOT	Portland Bureau of Transportation
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PII	personally identifiable information
PLDV	passenger light-duty vehicle
PM	particulate material
ppb	parts per billion
QA	quality assurance
RDM	robust decision making
RSU	roadside unit
SAEV	shared autonomous electric vehicle
SANDAG	San Diego Association of Governments
SAST	strategic assumption surfacing and testing
SAV	shared autonomous vehicle
SCAG	Southern California Association of Governments
SCMS	smart charging management systems
SI-LOC	signpost indicator level of concern
TMIP-EMAT	Travel Mode Improvement Program-Exploratory Modeling and Analysis Tool
TNC	transportation network company
TRID	Transport Research International Documentation
UAM	urban air mobility
UAS	uncrewed aerial system
UTM	uncrewed traffic management
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VDOT	Virginia Department of Transportation

VMT	vehicle miles traveled
VSSA	Voluntary Safety Self-Assessment
VTOL	vertical takeoff and landing
WAS	wheelchair accessible services
WAT	wheelchair accessible taxicab
ZEV	zero-emission vehicle

APPENDIX A

Analysis of Risk Priorities Across the Full Risk Register

This appendix provides a summary of priorities assigned across all the sources of risk identified in the risk registers reported in Chapters 3 through 6. It provides overviews of the distribution of the risk sources by priority score, agency goals, and technology. It should be noted that these results apply only to the risks included in the report's risk register, which are almost certainly not completely comprehensive, and are also based on the categorizations developed for this report. Therefore, these results may not be taken as predictive of how risks may evolve or their relative severity across technologies and goals.

Table A.1 and Figure A.1 show nine sources of risk that are classified as extreme on their risk priority score. The risk matrix calculations suggest that these risks should receive priority attention in deliberating risk management. Figure A.1 shows that most extreme priority risk scores affect the agency goals of equity, privacy and security, and safety.

From Table A.1, 26% of the risks have been assigned extreme or high priority, 36% are moderate-high, and 37% are graded as being moderate or low priority.

Distribution of Priority Scores by Agency Goal

Figure A.2 provides an inverse view of the data in Table A.1 and Figure A.1. All the risks identified in the full risk register are organized by agency goals and risk priority level. The agency goal of safety shows the largest number of sources of risk (18) to goal outcomes. Second comes the agency goal of equity (16), which also shows the largest number of extreme risks.

Distribution of Priority Scores by Technology Group

Table A.2, Figure A.3, and Figure A.4 summarize and display the priority scores for all the sources of risk found in the risk registers in Chapters 3 through 6.

The analysis in the charts now looks across the full set by the technology group to which a hazard is assigned. MOD/MaaS does not show any hazard that achieves the level of extreme or high priority. This does not necessarily imply that this technology may not currently pose any crucial issue compared to the other technology types. Rather, this is largely a reflection that MOD/MaaS is beyond its initial adoption phase with an existing body of information, experience, and regulation. Most of the risks associated with MOD/MaaS are assessed as low, suggesting that the risks are at an acceptable level but need to be monitored by agencies. New embodiments of MOD/MaaS technology that emerge in the future may score higher.

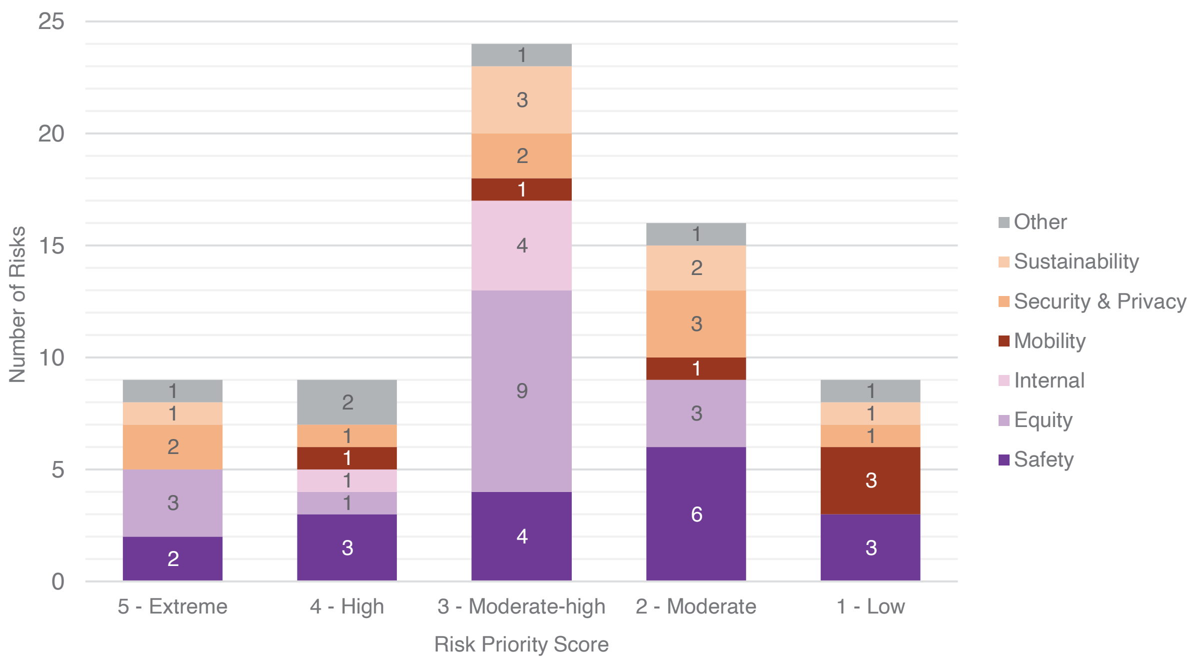
EVs and AAM technology formats contribute to most of the extreme and high-priority scores, followed by CAVs.

Table A.1. Summary of risk priority by agency goals.

Priority Score	Safety	Equity	Internal	Mobility	Privacy and Security	Sustain-ability	Other	Total	Share %
5 - Extreme	2	3	0	0	2	1	1	9	13
4 - High	3	1	1	1	1	0	2	9	13
3 - Moderate-High	4	9	4	1	2	3	1	24	36
2 - Moderate	6	3	0	1	3	2	1	16	24
1 - Low	3	0	0	3	1	1	1	9	13
Total	18	16	5	6	9	7	6	67	100

Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.

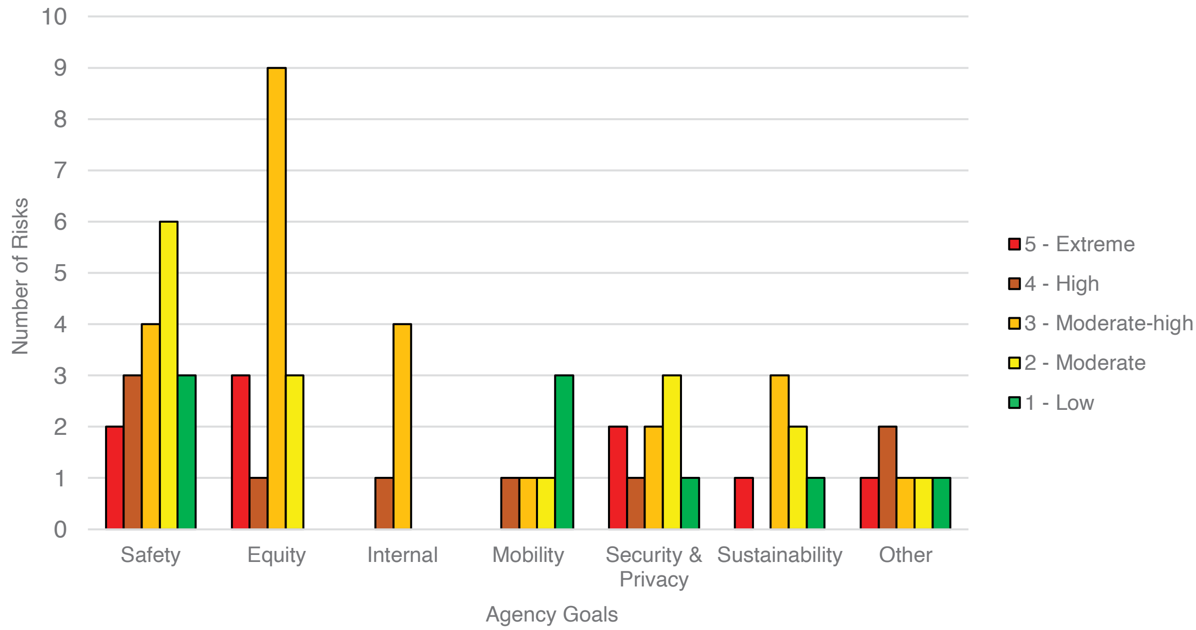
Source: RAND and Sam Schwartz.



Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.

Source: RAND and Sam Schwartz.

Figure A.1. Distribution of risks by their risk priority score, sorted by agency goals.



Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.

Source: RAND and Sam Schwartz.

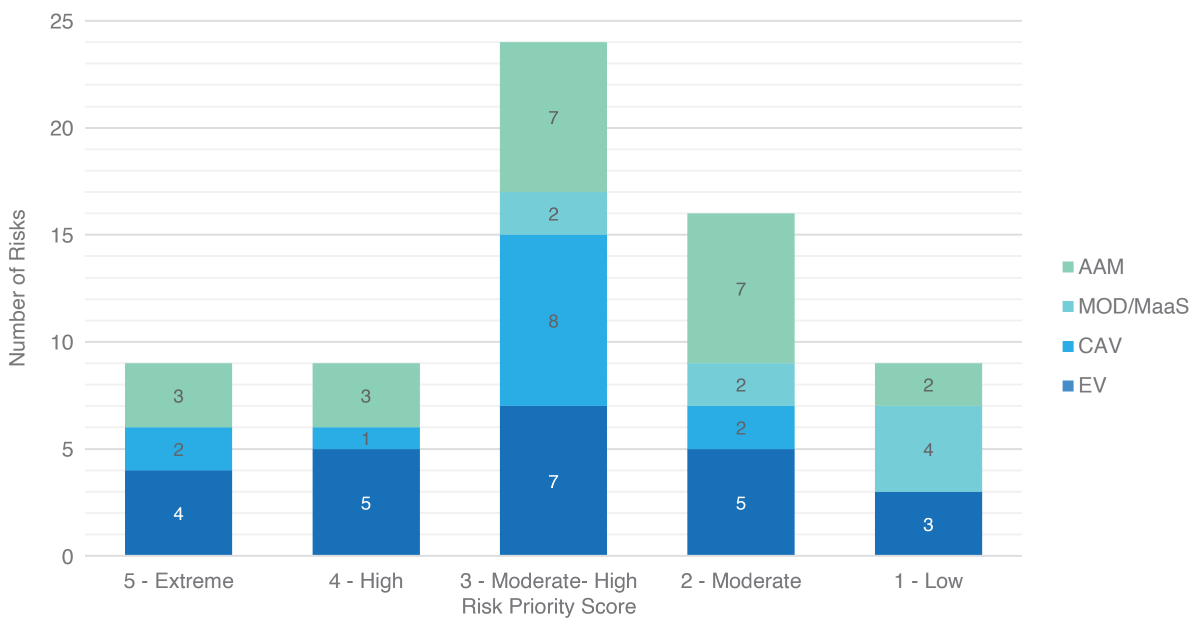
Figure A.2. Distribution of risks by agency goals, sorted by risk priority score.

Table A.2. Summary of risk priority by technology group.

Summary of Total Counts by Technology Group					
Technology Group	**EV**	**CAV**	**MOD/MaaS**	**AAM**	**Total**
Total Count	24	13	8	22	67
Unique Risk Sources	19	13	7	19	58
Summary of Individual Priority Scores by Technology Group					
Priority Score	**EV**	**CAV**	**MOD/MaaS**	**AAM**	**Total**
5 - Extreme	4	2	0	3	9
4 - High	5	1	0	3	9
3 - Moderate-High	7	8	2	7	24
2 – Moderate	5	2	2	7	16
1 - Low	3	0	4	2	9
Total	24	13	8	22	67

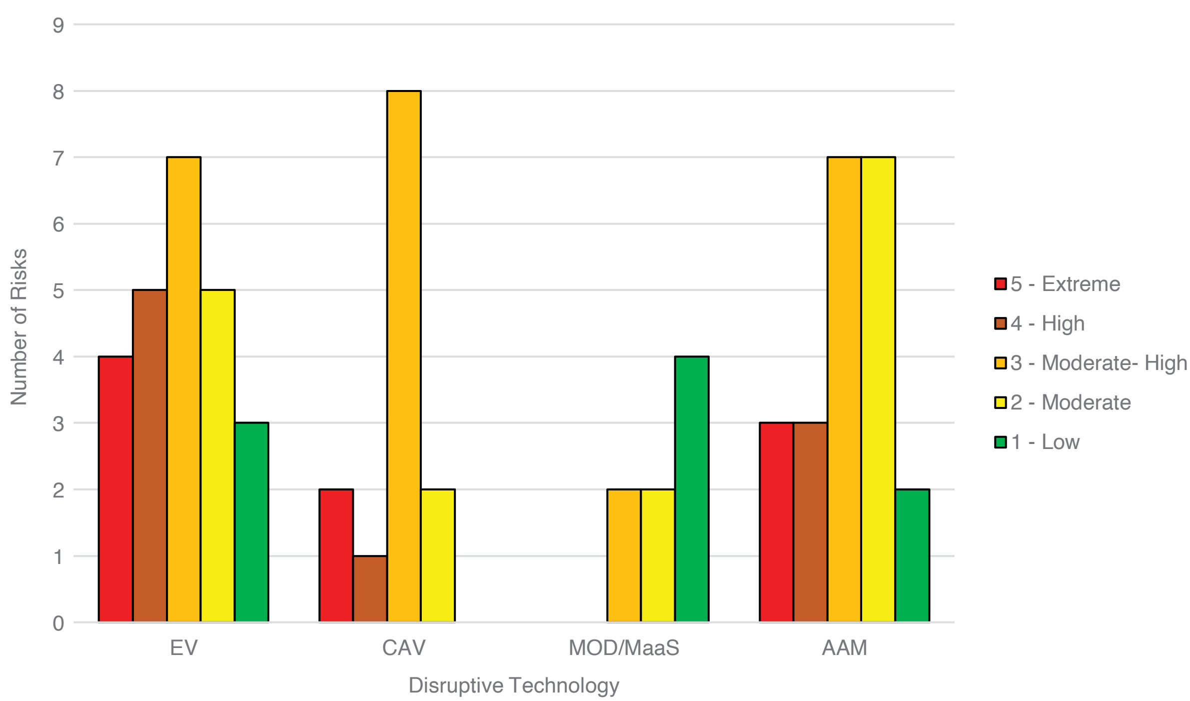
Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.

Source: RAND and Sam Schwartz.



Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.
Source: RAND and Sam Schwartz.

Figure A.3. Distribution of risks by risk priority score, sorted by technology group.



Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.
Source: RAND and Sam Schwartz.

Figure A.4. Distribution of risks by technology group, sorted by risk priority score.

Distribution of Agency Goals in Risk Register by Technology Group

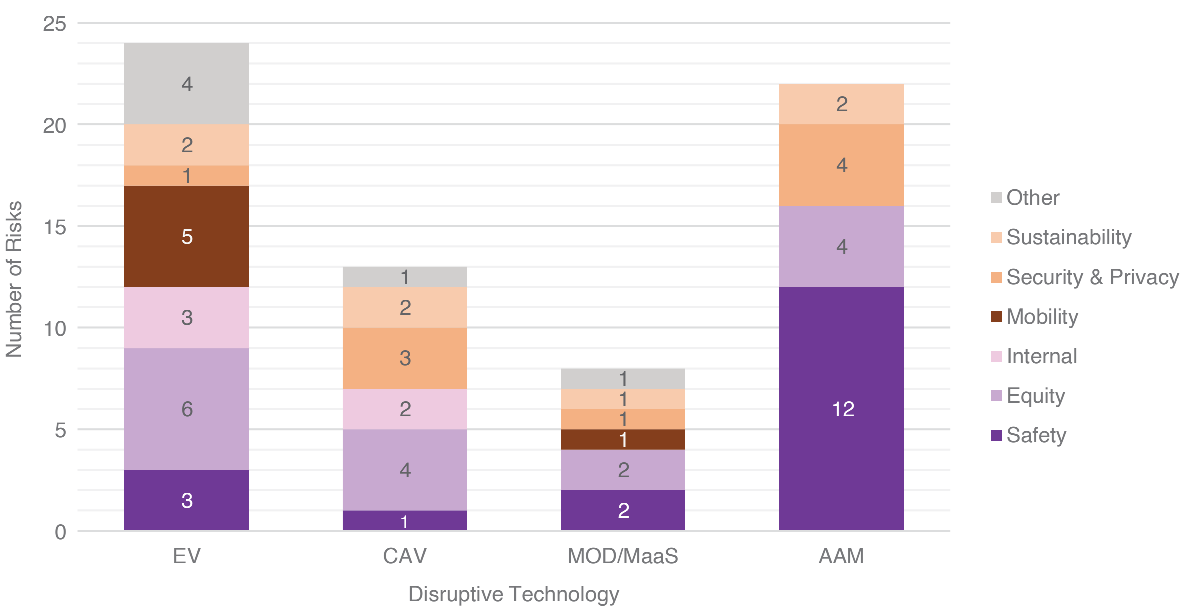
Table A.3, Figure A.5, and Figure A.6 provide a visualization of the relationship between agency goals and the four technology groups that were the subject of the report's research.

Based on the current risk assessment, the sources of risk for mobility goals arise from EV and MOD/MaaS technologies. EVs also appear to contribute the plurality of risks (6) to equity outcomes. Safety is the most ubiquitous concern across all four groups (18 of 67 total), but equity follows closely behind (16 of 67 total). AAMs contribute by far the most to safety concerns of all the technologies (12 of the 18), and AAM and CAV add the most risks to security and privacy (7 of the 9).

Table A.3. Distribution of sources of risk arranged by agency goal and technology group.

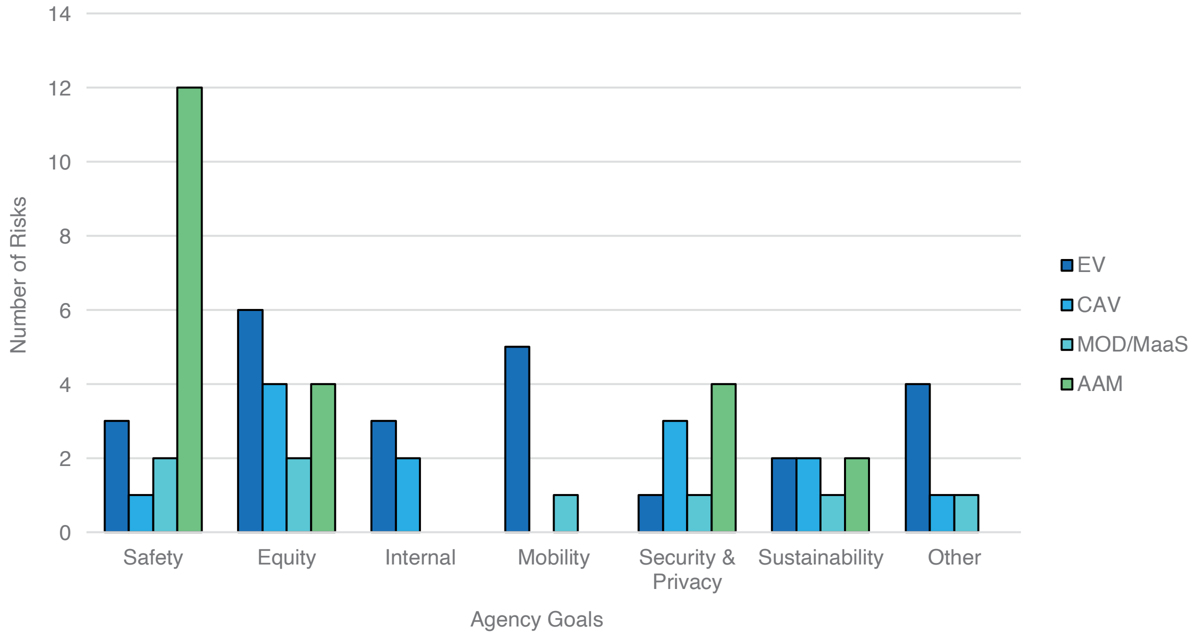
Agency Goals	EV	CAV	MOD/MaaS	AAM	Total
Safety	3	1	2	12	18
Equity	6	4	2	4	16
Internal	3	2	0	0	5
Mobility	5	0	1	0	6
Privacy and Security	1	3	1	4	9
Sustainability	2	2	1	2	7
Other	4	1	1	0	6
Total	24	13	8	22	67

Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.
Source: RAND and Sam Schwartz.



Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.
Source: RAND and Sam Schwartz.

Figure A.5. Distribution of risks to agency goals by technology group.



Note: The total number of priority scores exceeds the number of rows in the full risk register in Appendix B because more than one goal is ascribed to some of the risk register rows.

Source: RAND and Sam Schwartz.

Figure A.6. Risk distribution of disruptive technology within agency goals.

APPENDIX B

Full Risk Register Sorted by Agency Goals

Table B.1 compiles all the information found in the risk registers presented in Chapters 3 through 6. In Tables 3.2a, 4.1a, 5.1a, and 6.3a, all rows of the risk register are sorted by risk priority. Table B.1 aggregates all rows across the tables in Chapters 3 through 6, sorting them by agency goal and risk priority.

Table B.1 is intended to serve as a gazetteer allowing agency staff to swiftly locate the risk register rows that pertain to an area of concern. The row identifiers included in Chapters 3 through 6 are present in Table B.1 as well. Users can then consult the full register in Chapters 3 through 6. The appropriate rows in Tables 3.2b, 4.1b, 5.1b, and 6.3b will then yield further information on how the two likelihood proxies, the SI-LOC and CB-LOC, were evaluated.

The outward-facing agency goals are listed alphabetically in the column Goal Affected, followed by the listing of inward-facing goals. When it was judged that more than one goal could be ascribed to a hazard/technology pair constituting a row appearing originally in the tables found in Chapters 3 through 6, they appear as two separate rows in Table B.1. Therefore, the unique identifier may appear twice, once within each group representing the two goals. The content of those rows will be the same, differing only in the goal named in the Goal Affected column. No attempt was made to ascribe greater primacy to one goal over the other.

Table B.1. Full risk register sorted by agency goals and risk priority.

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
E1 Inequitable Payment System	Barriers to public charging station access due to payment options.	Contactless prepaid cash card adoption rate or track charging station payment options to understand the trend and options.	4	Equity	EV charging station payment option limiting certain users (e.g., unbanked, digital poverty, low credit score).	4	Establish or enhance the EVSE standards to ensure easy, reliable, and available access to all.	Federal and state DOTs and MPOs in collaboration with third-party survey providers.	**Extreme**
A2 Disparate Social and Environmental Impacts	Populations that have been made vulnerable bear a disproportionate burden of AAM impacts.	Demographics of people affected by AAM operations (e.g., flights and vertiports/takeoff and landing infrastructure).	3	Equity	Low-income households, minority communities, and other historically underserved populations bear disproportionate adverse effects of AAM operations (e.g., noise, visual pollution).	4	1. Incorporate environmental justice and disparate impact analysis as part of vertiport and airspace planning; consider conducting an analysis at regular intervals after implementing AAM service to determine whether changes are needed (e.g., routing). 2. Consider antidisplacement and gentrification policies in the vicinity of vertiports and intermodal passenger facilities with AAM.	U.S. DOT, FAA, state DOTs.	**Extreme**
E2 Exposure to Emissions	Disproportionate exposure to transportation emissions.	1. Diesel PM and NO_2 air quality data paired with DAC (diesel index from Justice40 map). 2. Commercial zero-emission truck registration data. 3. Access to commercial vehicle charging stations.	3	Equity	Continuing or worsening adverse health effects for communities exposed to transportation emissions.	4	Prioritize deployment of zero-emission MD and HD vehicles in the overburdened communities and better understanding of infrastructure needed.	State DOTs and MPOs in consultation with state environmental or energy departments and local jurisdictions.	**Extreme**
A6 Unaffordability of Services	AAM services are not mass-market affordable (passenger and aeromedical services).	Affordability of AAM services and use cases (e.g., per trip or mile metrics).	3	Equity	AAM services are only available to select users (e.g., business travelers).	3	1. Consider public policies that could enhance access or affordability to services (e.g., subsidies, essential air service programs). 2. Consider the regulation of areas such as fares, routes, and market entrants. 3. Consider taxing AAM to fund other types of mass-market transportation services (e.g., public transportation).	U.S. DOT, FAA, U.S. Congress.	**High**

E8 Inequitable Adoption	Inequitable EV adoption.	1. Access to charging stations (charger density compared to population density, geographical area, or population income level). 2. Drive times to nearest charger by low-income, urban, and rural communities). 3. Justice40 metrics for measuring charging access for DAC. 4. Number or amount per application of EV rebate between DAC and non-DAC.	2	Equity	1. Inequitable distribution of benefits from a cleaner transportation and energy system. 2. High transportation cost burden for remaining ICV users due to disproportionate cost share of legacy infrastructures, unreliable fuel supply, and unaffordability of petroleum fuels.	4	1. Include equity in EV incentive design such as point of sales rebates, including used EVs, streamlining the application process, and reassessing eligibility criteria to needs-based approach (income, air quality, etc.). 2. Ensure equitable access to affordable and reliable charging stations.	State DOTs and MPOs work with state legislative and environmental agencies.	**Moderate-High**
A8 Privacy Concerns Associated with Low-Altitude Flight	Residential communities concerned with low-altitude aircraft flying over homes and yards.	Privacy complaints from the community.	3	Equity	Privacy complaints along AAM routes, in the vicinity of vertiports, and around sensitive land uses.	2	Ban the use of various surveillance equipment, such as live-feed video cameras, infrared cameras, heat sensors, and radar on AAM aircraft.	FAA, state DOTs.	**Moderate-High**
A12 Visual Pollution	1. AAM creates unwanted visual disturbances, particularly for nonessential use cases that can be completed using ground. 2. Transportation options.	Aesthetic complaints from the community.	3	Equity	Aesthetic complaints along AAM routes, in the vicinity of vertiports, and around sensitive land uses.	2	Local governments implement design standards intended to conceal AAM from public view to the extent possible (e.g., setbacks, landscaping, form-based code, and design standards for vertiports).	Local government.	**Moderate-High**

(continued on next page)

Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
C6 Increased Car Ownership	CAVs increase private vehicle ownership.	Projected CAV rollout modality and trends in car ownership.	2	Equity	Adverse impact on accessibility across space (access increases in urban and suburban areas and decreases in external areas) and across social groups (driven by private CAV ownership and market-driven access disparities). Most literature suggests decreased private ownership in the long term (through subscription-based models, etc.) but high-end personal CAVs in 3 to 4 years.	3	1. Incentivizing shared CAV fleet deployment. 2. Tracking progress on transportation equity.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**
C7 Reduced Affordable Transportation Options	Reduction in affordable transportation options due to high up-front costs of CAV-ready infrastructure.	Trends in private CAV infrastructure (e.g., V2I technology, charging stations) investment vs. improvement in transit operations.	2	Equity	May exacerbate existing affordability/access considerations resulting in distribution equity challenges.	3	1. Investing in multimodal transit networks by integrating shared autonomous fleets with existing transit systems. 2. Ensure appropriate subsidies/incentivization of shared autonomous fleets over private vehicle ownership.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**
C8 Urban Deployment	CAV deployment is concentrated in urban cores.	Charging station density per 100,000 persons or square mile.	3	Equity	Investments in downtown cores may increase downtown land values and density while reducing land values and densities in the fringes. Might make urban living more desirable, increasing housing/parking/ congestion costs.	2	1. Investing in CAV-ready infrastructure such as EV charging stations and high-speed broadband/5G, may improve equitable access in rural areas. 2. Agency readiness self-assessment.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**
C11 Inequitable Opportunities	CAV deployment increases the opportunities gap across demographics.	Agency-specific opportunity gap analysis.	3	Equity	This hazard can result in perpetuating existing structural inequities across the transportation agency workforce.	2	Update recruiting, training, retraining, and succession management practices to attract a wider pool of talent.	State DOTs, MPOs.	**Moderate-High**

E10 Disparate Opportunity for EV induced jobs	Limited access to high-quality, clean transportation jobs in communities made disadvantaged.	Track clean energy job pipeline, job training, and enterprise creation in communities made disadvantaged on installing and maintaining EV charging infrastructure.	2	Equity	Inequitable access to economic opportunities and inequitable shift in the job market.	3	Forward-looking workforce planning policies, including equitable transition. 1. Early identification of trends in skills that may become in demand along with wider adoption of EVs. 2. Investment into workforce training and development, retraining programs for workers in the sectors displaced by EVs (i.e., mechanics). 3. Equitable workforce considerations.	Federal, state, and local DOTs, MPOs.	**Moderate-High**
E12 Unaffordable Energy	Electricity rate and affordability of charging.	1. Energy cost burden for DACs. 2. Transportation cost burden for DACs.	3	Equity	Modified or increased electricity rate increases burdens on low- and average-income households.	2	1. Consider adopting a regulation for technology solutions to alleviate grid constraints, such as power management systems like SCMS. 2. Integrate transportation electrification into grid infrastructure and resource planning.	State DOTs and MPOs in consultation with the state energy department.	**Moderate-High**
E13 Reduced Transit Service	Reduced affordable transportation options (e.g., less public transit, fare increase due to electrifying buses) due to investment and resource shift to electrification.	Commute time, no vehicle, and transportation costs for DAC (Justice40 map).	2	Equity	Reduced public resources in primary mobility modes for communities made disadvantaged.	2	Understand current state of the mobility burden and affordability of public transit for DACs and analyze the potential for reduced affordability due to vehicle electrification.	State DOT, MPO, and transit agencies.	**Moderate**
M3 Inequitable Access	Lack of accessibility.	Services or the number of vehicles do not meet demand for those with disabilities at a rate like those without disabilities. Some services (e.g., micromobility) are launched without addressing universal access.	2	Equity	Only populations with full abilities can access the full suite of MOD options.	2	1. Identifying minimums for accessible vehicles. 2. Creating a mobility fund to provide services for those with disabilities.	Providers, state DOTs, and local DOTs.	**Moderate**

(continued on next page)

Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
M4 Discrimination	Discrimination against protected classes.	Affordability of MOD services among all classes and income levels.	3	Equity	Limited access. Little/no access for populations that have been made vulnerable.	1	1. Identifying cost of services and affordability among classes that are served by transit and, in cases where it is not possible, identifying why. 2. Identifying circuit-breaker programs to ensure affordability for all classes and abilities.	MPOs and DOTs; social equity and justice organizations.	**Moderate**
E6 Unreliable Charging Service (Human)	Unreliable public charging service due to human behavior. 1. Fully charged EVs are not making space for other users. 2. EV-dedicated spaces are occupied, or conventionally fueled vehicles are parked in EV-dedicated spaces).	Customer feedback on reliability of service and wait time to get charged.	3	Mobility	Increased VMT to find available charging stations, increased wait time, compromised mobility.	3	Employ charging valet services for high-demand charging stations.	State DOTs and state agencies in collaboration with industry, charging station operations and maintenance, high-demand stations (e.g., airports).	**High**
E9 Unreliable Charging Service (Tech)	Unreliable public charging service due to technical issues and delayed service. 1. Improperly installed and maintained charging stations (i.e., insufficient cable length to accommodate certain vehicles). 2. Broken chargers, unresponsive or unavailable screen. 3. Lack of reporting or response system. 4. Insufficient workforce to respond to service requests.	1. Customer feedback on reliability of service. 2. Charger uptime. 3. Service lead time.	4	Mobility	Not getting the needed charge. User and worker injuries.	2	Establish charger reliability standards and service protocols, including communication systems, better training, prevention, and response safety technology/sensors, first responder training (electrocution), and notification.[f]	State DOT working with other state agencies and various stakeholders.	**Moderate-High**

E15 Exclusive Membership	Barriers to public charging station access due to exclusive membership requirement.	1. Consumer feedback and surveys. 2. Utilization rate per charging station, charging network, and membership requirement.	2	Mobility	1. Underutilization of public charging stations 2. More driving time to find the in-network charging options	2	Establish or enhance the EVSE standards to ensure easy, reliable, and available access to all.	Federal and state DOTs and MPOs in collaboration with third-party service providers.	**Moderate**
E17 Grid Failure	Grid and network failure can have a cascading impact on EV mobility (e.g., extreme weather events, cybersecurity).	Evaluation of EV charging station resilience (hazards, vulnerability, redundant energy supply, etc.).	1	Mobility	Compromised mobility and safety.	2	Assess vulnerability and consider resilience-improving measures (e.g., on-site generation and storage) for new and existing charging stations.	State DOT working with other state agencies and various stakeholders.	**Low**
E18 Lack of Supporting Functions	Lack of supporting functions to support EVs on the road and the policy goals (e.g., ICV sales ban).	Projections and availability of supporting functions (e.g., number of EV technicians).	1	Mobility	1. Compromised mobility due to the lack of EV technicians, roadside assistance for battery depletion. 2. High unemployment or job loss for traditional vehicle-supporting functions.[g]	2	Funding allocation and program implementation in workforce retraining.[h]	State legislatures and state DOT in collaboration with other agencies.	**Low**
M7 Increased Congestion	Increased traffic congestion.	Related congestion data (e.g., Inrix, telematics).	1	Mobility	Risks of TNCs replacing high-occupancy modes and induced demand for MOD services.	2	Identify incentives for sustainable modes and caps on TNC trips at peak times.	State and local DOTs in partnership with MOD providers.	**Low**
E6 Unreliable Charging Service (Human)	Unreliable public charging service due to human behavior. 1. Fully charged EVs are not making space for other users. 2. EV-dedicated spaces are occupied or conventionally fueled vehicles are parked in EV-dedicated spaces).	Customer feedback on reliability of service and wait time to get charged.	3	Public Acceptance	Low acceptance for EVs.	3	Employ charging valet services for high-demand charging stations.	State DOTs and state agencies in collaboration with industry, charging station operations and maintenance, high-demand stations (e.g., airports).	**High**

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Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
E15 Exclusive Membership	Barriers to public charging station access due to exclusive membership requirement.	1. Consumer feedback and surveys. 2. Utilization rate per charging station, charging network, and membership requirement.	2	Public Acceptance	1. Underutilization of public charging stations. 2. More driving time to find the in-network charging options.	2	Establish or enhance the EVSE standards to ensure easy, reliable, and available access to all.	Federal and state DOTs and MPOs in collaboration with third-party service providers.	**Moderate**
E2 Exposure to Emissions	Disproportionate exposure to transportation emissions.	1. Diesel PM and NO_2 air quality data paired with DAC (diesel index from Justice40 map). 2. Commercial zero-emission truck registration data. 3. Access to commercial vehicle charging stations.	3	Public Health	Continuing or worsening adverse health effects for communities exposed to transportation emissions.	4	Prioritize deployment of zero-emission MD and HD vehicles in the overburdened communities and better understanding of infrastructure needs.[d]	State DOTs and MPOs in consultation with state environmental or energy departments and local jurisdictions.	**Extreme**
A1 Aircraft System Failure*	Critical aircraft system failure (e.g., degraded or loss of command and control, GPS, engine failure).	Incident reports and crashes with critical aircraft system failure as the proximate cause.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	4	Require redundant systems as part of aircraft and airworthiness certification to minimize reliance on a single critical system that could cause catastrophic failure.	FAA.	**Extreme**
A3 Aircraft Control Loss*	Loss of aircraft control (e.g., flight control system failure).	Incident reports and crashes with loss of aircraft control as the proximate cause.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	4	1. Require redundant systems as part of aircraft and airworthiness certification to minimize reliance on a single critical system that could cause catastrophic failure. 2. Improve aircrew and ground crew training and certification to minimize the proximate cause(s) of loss of aircraft control (e.g., maintenance issue) and improve the likelihood of a safe recovery.	FAA.	**Extreme**

A4 Software Failure*	Failure of autonomous and highly complex software.	Incident reports and crashes with software or computer systems failure as the proximate cause.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	3	Work with industry and the FAA to identify potential flaws in flight and airspace management software and autonomous systems.	FAA.	**High**
A5 Flying Outside Approved Airspace	Flight outside approved airspace.	Incident reports and crashes involving AAM operations in prohibited airspace.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	3	1. Improve airspace management processes and technologies, such as crew/air traffic control resource management, uncrewed traffic management (UTM), and providers of services of UAM (PSUs). 2. Work with DOD, DHS, and local law enforcement to strengthen enforcement mechanisms, such as aircraft interception, fines, and incarceration.	FAA.	**High**
E7 Battery Fire	Battery fire and explosion. 1. EV fires are more difficult to extinguish than ICV fires. 2. EVs submerged or damaged from a storm have a potential risk of a high-voltage electrical battery fire.	1. NHTSA investigations related to battery safety. 2. Vehicle recalls related to battery safety issues. 3. EV fire by cause.	3	Safety	Though the risk of fire or explosions is no greater than that of conventional vehicles, there still exists the potential for fires to spread to other vehicles and buildings near the point of charge or crash.	3	1. Implement safety requirements and best practices for EVSE, battery packs, and BMSs. 2. Establish fire suppression system guidelines for higher-impact charging stations (i.e., underground parking structures).	NHTSA in consultation with federal and state DOTs, MPOs.	**High**
A9 Unsafe Proximity to People and Property	Unsafe proximity of AAM operations to people or property.	Complaints from the public of incidents or crashes with injuries, loss of life, or loss of property due to AAM.	3	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	2	1. Improve airspace management processes and technologies, such as crew/air traffic control resource management, UTM, and PSUs. 2. Work with DOD, DHS, and local law enforcement to strengthen enforcement mechanisms, such as aircraft interception, fines, and incarceration.	FAA.	**Moderate-High**

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Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
C9 Increased crashes	CAV deployment causes an increase in traffic-related crashes.	Crash statistics from pilot CAV deployment.	2	Safety	Traffic-related crashes attributed to CAV rollout may increase reluctance to adopt CAVs and worsen negative public perceptions about CAVs.	3	1. VSSAs to demonstrate to the public and their respective states that they are: (a) considering the safety aspects of CAVs; (b) communicating and collaborating with federal agencies, such as DOT; (c) encouraging the self-establishment of industry safety norms for CAVs; and (d) building public trust, acceptance, and confidence. 2. Integrating traffic safety culture in agency planning processes.	State DOTs, MPOs, and local, tribal, territorial agencies, in consultation with NHTSA and private partners.	**Moderate-High**
M2 Road Crashes	Road crashes.	1. Crash data. 2. Fatal crash data.	3	Safety	Increased transportation crashes (and associated injuries/deaths).	2	Geofencing for high-conflict locations to slow or stop usage. Design and speed limit policy (20 is plenty).	State DOTs and MPOs work with local governments on policy and mitigation.	**Moderate-High**
A11 Terrorism	Ground and air incidents involving terrorism, sabotage, personnel or insider threats.	Incident reports involving terrorism, sabotage, personnel or insider threats.	2	Safety	Increase in the number of occurrences, injuries, or fatalities that affect or could affect AAM users, personnel, aircraft, or facilities.	3	1. Consider policies to help mitigate risks from terrorism, sabotage, and insider threats, such as personnel background checks. 2. Develop data sharing, security, and emergency response protocols for pre-, mid-, and post-flight.	TSA, law enforcement (local, state, and federal).	**Moderate-High**
A13 Ground Incidents	Ground incidents (e.g., FOD), electrocution, vehicle crash, falling objects, the risk of fires and explosions, conflicts between parked or taxiing aircraft and ground vehicles.	Incident reports and crashes involving ground personnel, vehicles, or parked and taxiing aircraft.	2	Safety	Increase in the number of occurrences that affect or could affect the safety of ground operations or result in a crash that causes death or serious injury, or in which the vehicle, aircraft, or ground facility receives substantial damage.	2	1. Conduct ground safety audits and implement policies and procedures to reduce the risk of personnel injuries and damage to aircraft, vehicles, and facilities. 2. Improve aircrew and ground crew training and certification to minimize the proximate cause(s) of ground safety incidents and minimize the severity of incidents should they occur. 3. Improve/enhance first-response capabilities to ground safety incidents.	FAA, state DOTs, first responders/ emergency management agencies.	**Moderate**

A14 Overwhelming Air Traffic Control	Transition between controlled and uncontrolled airspace overwhelms air traffic control.	1. Reports from airspace users of midair collision close calls or other congestion issues. 2. Increase in in-flight delays due to airspace congestion.	2	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	2	Establish procedures for resolving collision avoidance alerts, particularly between AAM and commercial (Part 121) aircraft.	FAA.	**Moderate**
E14 New Charging Tech	New charging technologies entering the market.	1. Surveys of consumers and employees working at charging stations. 2. investigations by federal agencies like the OSHA, NTSB, and NHTSA.	2	Safety	1. Improperly installed or maintained charging stations. 2. Exposure to electromagnetic fields.	2	Establish a streamlined and adaptive process to facilitate safety requirements and best practices for emerging charging technologies.	State DOTs and MPOs in consultation with state energy agencies and electric utilities.	**Moderate**
A15 Human Error	Human error as part of onboard or on-ground operations. The transition to full autonomy which may include operations centers with remote operators controlling multiple aircraft could create challenges associated with remote operator resource management (e.g., task saturation, miscommuni-cation, and loss of situational awareness).	Incident reports and crashes with human error as the proximate cause.	1	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	3	Work with industry and the FAA to enhance aircrew practices to reduce the likelihood and severity of human error.	FAA.	**Moderate**

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Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
A16 Passenger Incidents	Ground and air incidents involving unruly, unsafe, or disruptive passengers.	Incident reports involving unruly, unsafe, or disruptive passengers.	1	Safety	Increase in the number of occurrences that affect or could affect AAM users, personnel, aircraft, or facilities.	3	1. Consider policies to help mitigate risks from unruly, unsafe, disruptive passengers such as (a) passenger background checks, (b) no-fly lists for people convicted of certain criminal offenses; (c) passenger rating systems; (d) emergency dispatch buttons (to report unsafe or questionable behaviors). 2. Develop data sharing, security, and emergency response protocols for pre-, mid-, and post-flight.	TSA, law enforcement (local, state, and federal).	**Moderate**
A17 Cybersecurity	Cybersecurity risks (e.g., hacking).	Incident reports and crashes with hacking as the proximate cause.	1	Safety	1. [Safety] Increase in the number of occurrences or severity of cyberattacks that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage. 2. [Security] Increase in the number of cyberattacks that affect or could affect AAM operations, reliability, or data security.	3	Work with industry, the FAA, CISA, and other federal agencies to develop AAM cybersecurity standards and detection systems to mitigate the likelihood and severity of a cyberattack, and quickly identify an attack should one occur.	FAA.	**Moderate**
A18 Congestion	Airspace congestion.	1. Reports from airspace users of midair collision close calls or other congestion issues. 2. Increase in-flight delays due to airspace congestion.	1	Safety	Increase in the number of occurrences that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage.	2	Improve airspace management processes and technologies, such as crew/air traffic control resource management, UTM, and PSUs.	FAA.	**Low**

M6 Data Theft and Breaches	Data theft and breaches.	Data breaches that diminish MOD/MaaS mode share. Data breaches affect service delivery for MOD/MaaS.	1	Safety	User security.	2	Develop robust data security systems for system protection. Develop regulatory requirements to ensure providers are reporting breaches and their impacts regularly.	CISA; business affairs with support from DOTs.	**Low**
E19 Increased Crime	Increased crime around charging stations. Overnight charging stations can be a target for vandalism.	Criminal stats by charger type (level 2 vs. DCFC).	1	Safety	1. Compromised safety and security. 2. Increased vandalism.	1	Implement prevention measures and update codes and standards for charging stations.	DOT working with state and local jurisdictions.	**Low**
C1 Hacked Infrastructure	CAV-connected infrastructure is successfully hacked.	Projected vulnerabilities of infrastructure/ industrial control systems.	4	Security and Privacy	1. Targeted congestion during on-ramp merging on highways (Zhao et al. 2021). 2. Life-threatening consequences of attacks that compromise a platoon of CAVs causing fatal crashes (Khattak et al. 2021). 3. Negative impacts on human safety and loss of PII (Hodge et al. 2019).	4	Invest in CAV infrastructure: upgrade cybersecurity protocols and conduct regular security audits and stress tests.	State DOTs and MPOs with potential matching federal funds.	**Extreme**
C2 Hacked Vehicle	CAVs are successfully hacked.	Projected vulnerabilities of CAV technologies (e.g., vehicle sensors, Internet-connected/edge devices).	4	Security and Privacy	In addition to allowing the attacker to access PII and use it for financial benefit (e.g., to redirect payments from charging or carry out denial-of-service attacks via CAV charging communication channels) (Hodge et al. 2019).	3	1. Increasing cybersecurity awareness. 2. Protecting the boundary between CAVs and transportation infrastructure.	Federal/state/local DOTs, MPOs.	**Extreme**
E4 Hacking Charging station	Successful hack of charging stations or EVs.	1. Increased incidents of data theft. 2. Number of cyberattacks by vehicle make, charging network, and payment systems.	3	Security and Privacy	1. Cyberattacks that could produce: (a) Data theft and fraud, (b) Denial of charging services, (c) Malware spread.	3	1. Establish standards for automated and connected systems and technologies. 2. Strengthen system response and recovery plans.	Industry, government agencies.	**High**

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Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
A7 Privacy	Private data is shared in an unauthorized way or with an unauthorized recipient.	Sensitive data is shared, leaked, or hacked.	2	Security and Privacy	User, financial, location, trip, or other sensitive data are improperly handled, stored, shared, or hacked.	3	Implement data security standards and regulations governing handling and management of sensitive AAM data.	FAA, Federal Trade Commission, Federal Communications Commission, state DOTs.	**Moderate-High**
A11 Terrorism	Ground and air incidents involving terrorism, sabotage, personnel or inside threats.	Incident reports involving terrorism, sabotage, personnel or insider threats.	2	Security and Privacy	Increase in the number of occurrences, injuries, or fatalities that affect or could affect AAM users, personnel, aircraft, or facilities.	3	1. Consider policies to help mitigate risks from terrorism, sabotage, and insider threats (e.g., personnel background checks). 2. Develop data sharing, security, and emergency response protocols for pre-, mid-, and post-flight.	TSA, law enforcement (local, state, and federal).	**Moderate-High**
C13 Data Privacy	Big data from CAVs raises ownership and privacy concerns.	Benchmarking against global standards for privacy/ cybersecurity.	2	Security and Privacy	Illegal data access can breach user privacy (e.g., travel behaviors, routes, personal information) and aggregated user data can also be used in nefarious ways for political purposes (e.g., identifying voting preferences, targeted advertising).	2	1. Robust risk assessment measure. 2. QA checks.	State DOTs, MPOs.	**Moderate**
A16 Passenger Incidents	Ground and air incidents involving unruly, unsafe, or disruptive passengers.	Incident reports involving unruly, unsafe, or disruptive passengers.	1	Security and Privacy	Increase in the number of occurrences that affect or could affect AAM users, personnel, aircraft, or facilities.	3	1. Consider policies to help mitigate risks from unruly/unsafe/disruptive passengers such as (a) passenger background checks; (b) no-fly lists for people convicted of certain criminal offenses; (c) passenger rating systems; (d) emergency dispatch buttons (to report unsafe or questionable behaviors). 2. Develop data sharing, security, and emergency response protocols for pre-, mid-, and post-flight.	TSA, law enforcement (local, state, and federal).	**Moderate**

A17 Cybersecurity	Cybersecurity risks (e.g., hacking).	Incident reports and crashes with hacking as the proximate cause.	1	Security and Privacy	1. [Safety] Increase in the number of occurrences or severity of cyberattacks that affect or could affect the safety of operations or result in a crash that causes death or serious injury, or in which the aircraft receives substantial damage. 2. [Security] Increase in the number of cyberattacks that affect or could affect AAM operations, reliability, or data security.	3	Work with industry, the FAA, CISA, and other federal agencies to develop AAM cybersecurity standards and detection systems to mitigate the likelihood and severity of a cyberattack, and quickly identify an attack should one occur.	FAA.	**Moderate**
M6 Data Theft and Breaches	Data theft and breaches.	Data breaches that diminish MOD/MaaS mode share. Data breaches affect service delivery for MOD/MaaS.	1	Security and Privacy	User security.	2	Develop robust data security systems for system protection. Develop regulatory requirements to ensure providers are reporting breaches and their impacts regularly.	CISA; business affairs with support from DOTs.	**Low**
E3 Delayed Buildouts	Delays to charging station buildouts: 1. Permitting and interconnection process. 2. Grid constraints limit charging station buildout.	1. Lead time for charging station development to completion. 2. Differing EV adoption rates in neighboring jurisdictions indicated by EV registration data.	4	Sustainability	1. Delayed EV deployment and failure to meet the GHG reduction goals. 2. DAC lacks charging Infrastructure.	3	Streamline and increase transparency for the permitting and interconnection process.[e]	State legislatures; hosting utilities; and federal and state agencies.	**Extreme**
C4 Increased Congestion	CAV deployment increases congestion.	Pre- and post-deployment metrics (such as VMT, vehicle occupancy rates, GHG emissions) from scientific literature.	2	Sustainability	The impacts from light-duty CAVs range from overall and CAV-related VMT, energy usage, and GHG and criteria pollutant emissions, depending on factors such as travel demand patterns, CAV-deployment modalities, and CAV technologies used.	4	1. Prioritize multimodal transit networks: integrating shared autonomous fleets with existing transit systems reduces total person travel time and incentivizes use of public transit. 2. Shared autonomous fleets also result in more equitable access to CAVs for low-income populations.	State DOTs, MPOs, and local, tribal, territorial agencies.	**Moderate-High**

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Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
A10 Scaled Operational Noise	Scaled aircraft operations create a noise nuisance.	Noise complaints from the community.	2	Sustainability	Noise complaints along AAM routes, in the vicinity of vertiports, around sensitive land uses, or during certain times of day.	3	1. Establish or strengthen noise standards for AAM aircraft. 2. Permit restrictions on the hours of AAM operations for nonessential use cases over sensitive land uses.	FAA.	**Moderate-High**
M1 Air Pollution and GHG emissions	Pollution/GHG emissions.	1. GHG calculated by VMT on MOD services. 2. Localized GHG calculated by usage.	3	Sustainability	Increased GHGs and localized pollution from MOD services.	2	1. State guidelines on what percentage of the fleet must be ZEVs each year. 2. Rules on when all MOD/MaaS vehicles must be zero emission. 3. Identification of power source for EV charging.	State DOTs, local DOTs.	**Moderate-High**
C12 Air Pollution and GHG Emissions	CAV adoption hinders agency goals regarding GHG/air pollution (PM2.5, nitrogen oxides/sulfur oxides) emissions reduction.	Correlation of ambient pollution with traffic volume.	2	Sustainability	1. Failure to meet agency goals regarding sustainability and climate change. 2. Reduced federal and state funding.	2	1. Clarify CAV testing, deployment, and operation guidelines for private-sector stakeholders. 2. Require prospective studies on CAV-related emissions costs/benefits for testing/operation.	State DOTs, MPOs.	**Moderate**
E16 Low EV Adoption	Low EV adoption.	1. Monthly/annual EV sales. 2. New vehicle registrations. 3. Carbon intensity of electricity.	1	Sustainability	Failure to meet GHG reduction targets.	3	1. Provide incentives to scrap older, high-polluting cars and replace them with ZEVs (California Air Resources Board 2022a). 2. Promote electrification of MD and HD[b] vehicles. 3. Assess the projected charging need for daily charging, road trips, ride-hailing, MD and HD electrification, and off-road, port, and airport electrification.	State DOTs and MPOs collaborate with other state agencies (environment, air quality, energy, etc.) and industry.	**Moderate**
A19 Aircraft Noise	An aircraft creates a noise nuisance.	Noise complaints from the community.	1	Sustainability	Noise complaints along AAM routes, in the vicinity of vertiports, around sensitive land uses, or during certain times of day.	2	1. Establish or strengthen noise standards for AAM aircraft. 2. Permit restrictions on the hours of AAM operations for nonessential use cases over sensitive land uses.	FAA.	**Low**
C3 Agency Workforce Obsolescence	CAV deployment increases the skills gap across the workforce.	Agency-specific skills gap analysis.	3	Workforce	This hazard can result in higher rates of retirement, higher obsolescence of skills in existing workforce, and unforeseen budget requirements for agencies.	3	Target foreseeable human resource requirements for data-centric jobs (data science, curation, analytics, and business intelligence), and improve attractiveness through revised compensation, particularly for contract/temporary workforce.	State DOTs, MPOs.	**High**

E10 Disparate Opportunity for EV induced jobs	Limited access to high-quality, clean transportation jobs in communities made disadvantaged.	Track clean energy job pipeline, job training, and enterprise creation in communities made disadvantaged on installing and maintaining EV charging infrastructure.	2	Workforce	Inequitable access to economic opportunities and inequitable shift in the job market.	3	Forward-looking workforce planning policies, including equitable transition: 1. Early identification of trends in skills that may become in demand along with wider adoption of EVs. 2. Investment into workforce training and development, retraining programs for workers in the sectors displaced by EVs (e.g., mechanics). 3. Equitable workforce considerations.	Federal, state, and local DOTs, MPOs.	**Moderate-High**
M5 Exploited Workforce	Exploited workforce.	1. Workers are not making a living wage. 2. Workers fall below the average median income for full-time work.	2	Workforce	Potential for unsafe operations if workers need to have multiple jobs.	1	Set regulations to ensure fair wages are established.	State DOTs, local DOTs, local workforce agencies.	**Low**
E5 Fuel Tax Revenue Decline	Declining in fuel tax revenue from increasing EV adoption rates.	1. EV registration rates. 2. HTF minimum prudent amount.	3	Internal—Budget	Expecting over $1B in revenue lost annually by 2030.	3	Design alternative tax schemes for EVs while considering consistency with neighboring states and equity.	State and federal DOTs, MPOs; state and federal legislatures.	**High**
C10 High Up-Front Cost Needed	CAVs require unforeseen investments in physical and digital infrastructure.	Net present value/financial analysis based on CAV-deployment costs (labor, infrastructure, etc.).	2	Internal—Budget	This hazard can result in transportation agencies running the risk of cost and time overruns for capital projects.	3	Budget provisions and updated design guidelines: MPO and DOT budgets and current design standards and guidelines for infrastructure should include provisions for future V2I and I2V investments in addition to known investments in CAV-friendly roadway markings, visible or retroreflective signage, and barriers between other road users and CAVs.	State DOTs, MPOs, and local, tribal, territorial agencies in consultation with third-party contractors.	**Moderate-High**
E11 Insufficient Investment Decision Capability	Various technical expertise, staff capacity, and right-of-way policies across local jurisdictions. Challenges on charging station deployment and EV technology.	EV charger utilization rates, charging station revenue, etc.	2	Internal—Budget	Charging infrastructure stranded assets (insufficient and unsustainable revenue from charging service).	3	1. Provide aid and support to state DOTs with fewer resources. 2. Provide data, guidelines, and tools that can be used for local agencies to support robust planning processes (e.g., Justice40 map, NAVI guidelines).	Federal DOT.	**Moderate-High**

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Table B.1. (Continued).

Risk Source by Technology Group	Potential Sources of Risk			Consequences for Transportation Agency Goals			Transportation Agency Policies and Actions		Priority Score
	Risk Source [Hazard]	Signpost Indicators to Watch	Likelihood Proxy	Goal Affected	Potential Consequences	Severity Score	Potential Mitigating Actions	Action Owners	
C5 Liability and Preemption Concerns	State-specific CAV regulations pose liability and preemption concerns.	Past tort liability cases (specifically for Level 3/4) vehicles) for claims, precedents, and legal outcomes.	4	Internal—Tort Liability	Liability claims such as those arising from negligence, misrepresentation, design defect, failure to warn, etc.	2	Seek legislative clarity on state tort laws. Generally, researchers contend that states can take the lead in regulating testing, and administrative procedures, such as licensing, without much risk of preemption. However, NHTSA is highly likely to preempt in cases of safety violations.	State DOTs, MPOs, and local, tribal, territorial agencies in consultation with DOT (FMCSA/NHTSA).	**Moderate-High**
E11 Insufficient Investment Decision Capability	Various technical expertise, staff capacity, and right-of-way policies across local jurisdictions. Challenges on charging station deployment and EV technology.	EV charger utilization rates, charging station revenue, etc.	2	Internal—Workforce	Charging infrastructure stranded assets (insufficient and unsustainable revenue from charging service).	3	1. Provide aid and support to state DOTs with fewer resources. 2. Provide data, guidelines, and tools that can be used for local agencies to support robust planning processes (e.g., Justice40 map, NAVI guidelines).	Federal DOT.	**Moderate-High**

*Note: The FAA's Aircraft Certification Service will require this likelihood to be extremely remote. These risks/hazards are already being considered as part of the type certification process. Type certification is the approval of the design of the aircraft and all components (including propellers, engines, control stations, etc.).

CISA: Cybersecurity and Infrastructure Security Agency.
(a) Disadvantaged communities (DACs) are defined by the Office of Management and Budget (OMB)'s Interim Guidance (The White House 2021b).
(b) Medium duty and heavy duty.
(c) E-commerce boom and increasing logistic needs add more air pollution burden on the communities already reside in the poor air quality area (i.e., near distribution centers and major highways, port, airport, etc.).
(d) California's medium- and heavy-duty vehicles cover a broad spectrum of duty cycles and use cases, including passenger travel, goods movement, port cargo handling, long-distance transport of refrigerated goods, and urban delivery, among many others. Charging infrastructure planning for the medium- and heavy-duty sectors requires close attention to the specific vehicle duties and environments, impacts of high-power charging demand, lack of consistency in charging connectors, limitations on available truck parking, and landlord-tenant relationships.
(e) CA AB 1236 and Rule 21: AB 1236 a permitting guidebook was published, and it includes optimal permitting process, current restrictions, and information regarding "permit ready" local jurisdictions. Rule 21 is a comprehensive standard policy for accelerated and streamlined interconnection process for rooftop solar integration.
(f) Reliability of Open Public Electric Vehicle Direct Current Fast Chargers (2022).
(g) Posky (2022).
(h) By 2040, California projects that nearly 32,000 auto mechanics jobs will be lost. California AB 1966 aimed to create a state fund to help retrain and transition workers from the fossil fuel industry to other non-polluting sectors.

Source: RAND and Sam Schwartz.

APPENDIX C

Methodology for Risk Management Assessment

Project Research Plan and Methods

This report largely concerns itself with presenting findings in the forms of risk registers for sources of risk from emerging and disruptive technologies; an assessment of risk priorities; and high-level policy guidelines for creating more agency resilience to emerging risks. But it also presents a framework and method that may be used by agencies going forward. This appendix presents an outline of the approach taken in this report to develop the materials presented.

The initial task was to conduct a literature review. Those sources that proved informative during this research are listed in this report's Bibliography. The purpose of the scan was to define the technological innovations detailed in the preceding section which have already had observable effects and are anticipated to increasingly affect a broad range of transportation goals. The research team produced four literature reviews that include agency, professional society, and academic journal websites using keywords to specify aspects of risk (e.g., safety, privacy, equity), risk management (e.g., risk, uncertainty, liability, threat), and transportation technologies (CAVs, EVs, MOD/MaaS, and AAM). Databases consulted included Google Scholar, Transport Research International Documentation (TRID) Online, Web of Science, LexisNexis, and ongoing work being conducted through the TRB. The research team contacted agencies with a request for information, including references to any publicly available documents that describe risk management practices or the potential for risks from these technologies.

After the literature review, the research team culled the findings into a core set and created a framework for them. The team segmented the information by technology, or combination of technologies, in a manner consistent with the risk/hazard paradigm. This framework became the risk register. The team also consulted literature on risk management methodologies.

The literature scan allowed the research team to elucidate gaps (in the form of unanswered questions) which motivated questions and themes for subsequent peer exchanges with a range of transportation professionals, researchers, stakeholders, and government staffers. This research conducted three such peer exchanges in April 2022 focused on mobility and safety, sustainability, and equity. The topics were selected based on the areas that appeared to require the most elucidation and that would also provide a valuable interactive experience for the attendees.

Each peer exchange had 8 to 12 participants per session. These included attendees who worked on planning and policy staffs of state DOTs and MPOs and representatives of other government agencies but also included researchers, staff of NGOs, and representative stakeholders from both business and local communities. Over the 2-hour sessions, attendees were presented with the outlines of the project and a brief tutorial on risk. Using a specifically tailored Mural (2022) whiteboard application, the attendees were asked to participate in two activities that allowed them to put individual "sticky notes" on a prepared virtual whiteboard as well as to engage each

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other in discussion. In the first activity, attendees were presented with a form listing the four technology groups as well as a fifth labeled "Cross-Cutting/Combined Technologies." Each of the five blocks was divided into three rows marked: hazards, consequence, and likelihood. Attendees would place a virtual sticky note in the top (hazard) row—or address one placed there by others—and then arrange comments on consequences and likelihoods corresponding to that hazard. The second activity was to use Mural (2022) to frame a conversation around how agencies can respond to disruptive technologies, better manage risk, and what elements of best practice exist that should be examined for wider adoption.

Using outputs from the peer exchanges and the results of the literature review, the research team identified the hazards to be included in the risk register. These hazards included potential deleterious outcomes from the application of the new technologies as well as missed opportunities for failing to advance agency goals through technology use. The peer exchanges were conducted virtually under Chatham House rules and with the oversight of the RAND Human Subjects Protection Committee protocols. The exchanges allowed the team to collect further data on additional risks identified by practitioners and academia as well as best practices and mitigation strategies. The team assimilated the collected data with the results from the literature review to develop an internal summary of risks categorized by agency goals.

A draft framework of the risk register was developed and refined over several iterations. Care was taken to adapt the risk register to an environment where little data on probability and scale of hazard occurrence were available. What the research team strove to develop and present is an adaptable tool for users, as opposed to a conclusive final list of hazards, risks, and priorities.

The second product of the data-gathering step was the development of high-level policy and strategy primers aimed at presenting broader, high-level risk mitigation strategies and policies sufficient for implementation in a technology-agnostic manner across agency goals. The goal was to come up with a small set of such strategies that would inform agencies on steps that could make their organizations and processes more resilient to emerging risk and the dynamics of change. These were constructed by first analyzing the columns in the risk register that listed actions that could be taken to mitigate the consequences from the risks implicit in each of its rows. The research team noted commonalities across the mitigation strategies for the four innovative technologies, extracted input from the peer exchanges, and added insight gathered throughout the work.

The research also presents in detail the methodological elements developed by the research team. These are intended to help make transportation policies and actions more robust to the vicissitudes of changes in future technological trends, transportation outcomes, and expectations on the part of society for how transportation agencies need to adapt and perform in the future. These methods provide an entry point for agencies and their staff to investigate how to better manage and adapt their processes to a future that includes emerging and disruptive technologies.

The sum of the components provides value to DOTs and MPOs through a new framework to strengthen agency resilience to emerging technologies. While there are volumes written on new mobility, the combination of these components offers a holistic approach for agencies to proactively manage existing and new emerging technologies.

Agency Goals: What Is at Risk?

What complicates this assessment is that the agencies themselves are rarely the principal investors in or instigators of potentially disruptive technological change. In recent years, transportation innovations have changed modal use patterns, and this is expected to continue. New forms of micromobility and shared mobility have led to modal shifts as well as induced demand. Most of these mobility technologies have been introduced by the private sector. While private companies may have missions that align with a transit agency, MPO, or DOT goals, the bottom line is that private companies must meet their financial obligations and, ideally, return a profit. This bottom line may lead to applications of new technologies that could place agency goals at risk. This was the case in 2014 when Uber and Lyft began providing services similar to those offered by public transit agencies to expand market share (Bercovici 2014).

And as with any innovative technology, there may be unintended consequences. A company may seek to provide a solution intended to further regional sustainability and mobility goals but could unintentionally adversely affect those goals or other agency goals in the long run. One step in protecting these goals is having a common agency definition for the goal and an understanding of what is at risk when faced with the changes emerging mobility technologies may bring.

Equity

The U.S. DOT has centered equity as a strategic goal in its recently released Strategic Plan (2022). In this plan, the equity goal seeks to "reduce inequities across our transportation systems and communities they affect. [It also seeks to] support and engage people and communities to promote safe, affordable, accessible, and multimodal access to opportunities and services while reducing transportation-related disparities, adverse community impacts, and health effects" (U.S. DOT 2022d). One critical component of equity is racial equity which targets the disparities created by historic planning practices and systemic racism. Other aspects of equity aim to tackle the systemic inequities facing identities defined by characteristics including gender, age, ability, and income. Transportation agencies and DOTs are recognizing that communities may require different enhancements to contribute equitably to the mobility ecosystem. If an agency's equity goals are not met, inequitable access to opportunities may result, and there may be an unequal distribution of health and quality of life effects from the transportation system.

Safety

Reduction and elimination of fatality and injury is the number one priority of the U.S. DOT. Each operating administration under U.S. DOT's jurisdiction takes a safety-first approach to providing transportation services. The Federal National Roadway Safety Strategy, issued in 2022, is intended to manage safety risks and hazards that may arise within the country's streets and highways. Qualifying agencies that receive federal funding must create safety performance targets to ensure safety enhancements are being realized (FTA n.d.). In recent years, agencies have also begun to work toward Vision Zero. The Vision Zero concept, first adopted in Sweden, acknowledges that even just one death resulting from within a transportation system is unacceptable. It utilizes the Safe System Approach, which relies on designing and managing road infrastructure to keep the risk of mistakes low. The five pillars of the Safe System Approach—safe vehicles, safe speeds, safe roads, postcrash care, and safe road users—proactively tackle different aspects of the roadway infrastructure and its operation that expose humans to vulnerabilities (FHWA 2020). Before committing to Vision Zero's Safe System Approach, an agency must first commit to a safety culture, which can be defined as "shared values, actions, and behaviors that demonstrate a commitment to safety over competing goals and demands" (U.S. DOT 2020). If an agency's posture toward safety cannot keep up with the pace novel mobility technologies are setting, system and traveler safety may be compromised as a result.

Environment and Sustainability

The U.S. DOT Strategic Plan's climate and sustainability goal acknowledges the role transportation plays in creating solutions to climate change. To increase the sustainability of the transportation system, agencies need to "substantially reduce GHG emissions and transportation-related pollution and build more resilient and sustainable transportation systems to benefit and protect communities" (U.S. DOT 2022d). Emerging mobility modes, especially those geared to greater shared transportation, are often seen as being more sustainable compared to a system based on personally owned ICE vehicles. If, however, they encourage more trips, the net result may be deleterious to agency sustainability goals. Long-term sustainability relies on putting policies and programs in place to encourage emerging mobility companies to fill gaps in and complement existing transportation services (California Department of Transportation 2022). Emerging mobility technologies could threaten an agency's sustainability goal by making it increasingly difficult or impossible to meet its GHG reduction or mode split goals.

Mobility

Mobility is the capacity to move quickly within and throughout a transportation environment to different activity sites. One means for enhancing mobility is accessibility, the number of activity sites available within a given distance or travel time (Giuliano and Hanson 2017, ch. 1). In the history of urban planning in the United States, distances between activity sites have lengthened due to suburbanization, ease of travel in private automobiles, and zoning codes that have led to spatial separation of activity sites. Historically, the goal in transportation planning has been to "increase people's mobility as *the* way to increase accessibility" (Giuliano and Hanson 2017, ch. 1). Today, however, key stakeholders acknowledge that increases in accessibility can also be achieved by integrating land use and transportation planning (Giuliano and Hanson 2017, ch. 1). Investments that lead to mobility benefits are critical to improving community well-being, and the distribution of mobility benefits must be distributed evenly to ensure improvements for all socioeconomic groups in a region (Golub et al. 2013). Emerging mobility technologies have the potential to increase congestion—and therefore reduce mobility—due to induced demand brought by lower operational costs, convenience, and access.

Security and Privacy

Maintaining security and privacy for individuals accessing the transportation system is imperative to agency goals. One major objective of the U.S. DOT's Strategic Plan is to "strengthen transportation system resiliency to protect it from disruption from cyber and other attacks" (U.S. DOT 2022d). This involves but is not limited to providing technical assistance to identify and address physical and cybersecurity vulnerabilities, incorporating cybersecurity protections into emerging connected systems and technologies, and strengthening response and recovery plans in the event of a security incident (U.S. DOT 2022d). Failure to maintain a secure transportation system could lead to connectivity challenges and individuals' compromised safety and privacy.

These five main outward-facing goals appear as their own categories in the risk register. Several others appear although they are not as ubiquitous across technologies. These include matters such as public acceptance of new technologies—how well and how readily the public accepts new technologies may be a factor in achieving other agency goals—and public health, a category used to include factors that would support or detract from public health other than those included in the category of safety. These less frequently mentioned issues appear in the risk register and the summary statistics in Appendix A as "Other."

Internal Agency Goals

Agencies also have several internal objectives. Agencies should individually or collaboratively define these goals so that they can then identify consequences that may result if the goal is compromised. The specific internal goals that emerged from the literature review and peer exchange sessions included budgetary solvency, tort liability, workforce adequacy (both within the agency in terms of access to necessary skills for understanding changed requirements associated with emerging technologies and within the wider economy for those technologies' safe and effective operation), data governance, and possible changes in agency missions and goals as a result of societal change from technology adoption. In the risk register framework, internal agency goals were treated as one larger set.

The Problem of Uncertain Likelihoods

The novel or even prospective nature of several of the technologies examined by this research and their potential sources for risk means that there is an absence of reliable estimates for the likelihoods associated with each hazard/technology/goal combination appearing in the risk register. The research team developed two different but complementary methods for constructing proxies for hazard likelihood emanating from emerging technologies. Neither proxy stands in for an actual calculation of probability. The team viewed the probability estimates normally found in risk registers as primarily being used as a measure of how much concern the risk managers should have for the hazards and consequences in the register."

That is, if the estimated severity of consequences for two different rows of the risk register are adjudged to be equal should the associated hazards appear, then the risk managers should have greater concern for the one to which a higher likelihood is attributed. The ascription of likelihood is a necessary element for determining overall priority of risk.

Of the two likelihood proxies used in this report, one derives from the suggested signpost indicators included in each row of the risk register that treats a specific hazard/technology/goal combination. This proxy, however, can only come into play when deployment is underway, a suitable metric is decided, and the necessary indicator data are generated. The other likelihood proxy stems from a qualitative assessment of the LOC that may be appropriate even before the deployment of a transportation technology based on the objective characteristics of that hazard/technology pairing. This would be used before the availability of data for calculating the signpost-based proxy for likelihood.

SI-LOC Measure

The first of the two approaches builds on one of the novel features of the risk register. Each row in the risk register presented in Chapter 4 proposes a signpost or signal indicator to be monitored for early warning that a specific foreseeable hazard may be arising as a transportation technology is deployed. The first likelihood proxy or measure expressing a calculated LOC would involve observation of the present state as well as the apparent trend over time of these respective indicators. Table C.1 shows how a measure would be developed on these principles.

The columns of the matrix in Table C.1 key off from the current measured state of the signpost indicator associated with the hazard/technology/goal combination in the risk register row being examined. "Target" means the result of a measurement that will have been previously set by either agency policy or agreed practice as being a trigger. It demarcates the level of the signpost measure at which the indicator becomes one of concern (e.g., "Congestion must not increase by more than 3%"). The rows in Table C.1 show the trend in the signpost indicator over time, most likely focused on the most immediate past data. The resulting score, rated 1 through 4, yields the SI-LOC; the higher the number, the greater the LOC as measured by the SI-LOC. For example, if the current state of the signpost indicator shows conditions that are out of the previously set range of tolerance for that variable, but the data are lacking to determine the trend over time ("indiscernible"), the SI-LOC measure would be set at 3. This reflects a design intent to be wary

Table C.1. Method for calculating SI-LOC measure (likelihood proxy).

		State of Signpost Indicator		
		On Target or within Tolerance	**Out of Tolerance**	**Substantially out of Tolerance**
Trend in Signpost Indicator	**Indiscernible**	2	3	4
	Strongly Negative	3	4	4
	Negative	2	3	3
	Positive	1	2	2

Source: RAND and Sam Schwartz design based on Rees et al. (2022).

of assuming the best (in this case, a "positive" trend.) In the presence of confirming evidence that the trend is strongly negative, the SI-LOC measure would be increased to a 4.

As may be seen by inspection of the concern classifications in Table C.1, the rows are privileged over the columns. That is, a trend moving in an unfavorable direction is viewed as cause for greater concern than a single unfavorable data reading at a specific time.

A risk register for emerging and disruptive technologies must be constructed as a dynamic tool. The principal benefit of the approach is that the target levels set for the signposts can be interpolated between observation of the experience gained by other agencies and the local and regional circumstances confronting specific agencies. The signpost indicators appearing in the risk register in Chapters 3 through 6 are intended to be suggestions that an individual agency can modify. The proposed proxy for likelihood will be grounded in what will previously have been selected as an appropriate signpost for how the deployment of a particular transportation technology is developing and what experience has been with individually identified sources of risk. Furthermore, given sufficient time series data, trends could be used to indicate a potential timeframe in which a metric may miss a target or fall out of tolerance.

The main downside of this approach to determining LOC is that it is data-based: The course of technology diffusion will already need to be underway to a degree sufficient to generate the data to be monitored. This shortcoming highlights the need for an alternative method for proxying likelihood before a deployment point that generates those data.

Characteristics-based Likelihood Proxy

The SI-LOC proxy mimics an empirical approach to estimating likelihood, similar to the data-based frequentist approach to probabilities used in statistics. The CB-LOC proxy identifies salient objective characteristics present in a hazard/technology combination and infers from them "How much should we be worried?" (This is sometimes referred to as a "hedonic" approach, one for which the magnitude of concern (in this case) is analyzed as being composed of several constituent parts.)

In this case, we seek a systematic, shorthand way of conveying the aspects of a hazard/technology/goal combination that an agency should be aware of in its risk management. The characteristic elements that compose the CB-LOC measure likelihood proxy arise from the typical questions agency risk managers ask before a technology's widespread adoption:

- Who might be affected by the source of risk? (The more people that can be affected, the greater the LOC. This consideration incorporates both direct users and those indirectly affected.)

- Is there enough time to respond to an emerging source of risk?
  - How quickly is the technology being implemented and when would we expect the hazard to be most likely to occur?
  - What capacities and capabilities would be required from agencies to take mitigating actions? How much preparation would be required?
- How much uncertainty surrounds the hazard?
  - How different is this hazard/technology combination from previous hazards?
  - Is it too novel to make useful recommendations?
  - Is there available information on the hazard or does new research need to be conducted?

Table C.2 shows how such a qualitative assessment of LOC might be combined to serve in a risk register for emergent, disruptive transportation technologies. This CB-LOC approach involves grading each hazard/technology/goal combination appearing in the rows of the risk register on five characteristics:

- **Novelty** is the innovativeness of the technology embodiment that could give rise to hazards. This assessment is largely timeframe agnostic and the governing element is not necessarily novelty per se but the size of the behavioral adjustment that might be required. Therefore, a system with many novel elements but in a largely preexisting platform might be the occasion

Table C.2. Assessing elements of the CB-LOC measure.

Dimension	Scale	Qualitative Assessment Guideline
Novelty	4	Many innovative elements embodied in a preexisting form
	3	Entirely innovative technology embodied in a new form
	2	Some innovative technologies embodied within existing, customary modes and processes
	1	Few novel elements involved
Velocity	4	Adoption rate is high; potential market is large
	3	Adoption rate is high, potential market may be small
	2	Adoption rate is low, potential market may be large
	1	Adoption rate is low, potential market is small
Size (affected)	4	Direct and indirect effects from hazard could affect total group
	3	Direct and indirect effects from hazard could affect sizable group
	2	Direct and indirect effects from hazard could affect small group
	1	Little or no effect to be expected beyond a narrow minimum
Information	4	Little or no information available
	3	Information gathering requires outreach to other agencies and early adopters
	2	Information available on selected basis in published literature or online sources
	1	Little or no concern about access to useful and timely information
Response	4	Consequences may be so challenging that mitigation is not feasible and fundamental systemic adaptation is required
	3	Mitigation requires acquiring new capabilities, resources, or external partnership
	2	Mitigation requires developing mitigation response to address
	1	Little or no concern about ability to mitigate or minimize in a timely manner or N/A

Source: RAND and Sam Schwartz.

for greater concern than something that is so clearly novel that users and operators are likely to exhibit greater caution and not make unjustified and potentially hazardous assumptions.

- **Velocity** is how rapidly the diffusion is occurring. This would be related to the current point along the near universal S-shaped technology diffusion curve that is typical in most cases of innovation adoption. The current point is a reference to the present adoption rate within the market. The speed varies at different points, and the eventual saturation point—at which adoptions over time level off—is not necessarily clear at the outset.
- **Size** refers to the population that may be directly or indirectly affected by the consequence stemming from the hazard/technology combination. This population may fluctuate over time as the technology adoption reaches critical tipping points and may be dependent on the jurisdiction in which the assessment is performed.
- **Information** is the amount of external experience or data available to the agency.
- **Response** is a measure of whether an agency might be able to develop the ability to put in place mitigating or limiting measures should the hazard occur. It is primarily an assessment of agency resources and capability for mitigation/adaptation, not timing per se, and is therefore timeframe agnostic.

Each is graded on a scale of 1–4, with 1 representing the least amount of concern and 4 representing the most. Table C.2 shows the scaling for the attributes to be included in this measure of concern. "N/A" means that the concern is outside of the realm of agency responsibility.

The grading choices along the five dimensions of hazard/technology/goal characteristics are measured within the timeframe most appropriate, as described above, and could be revisited in a future reassessment. Therefore, agencies will update their assessment using the Table C.2 scale at different intervals based on both changing general knowledge and awareness of the local circumstances within the region they serve.

State DOTs, MPOs, and local agencies will be in the best position to determine a score within the parameters of a qualitative tool such as the CB-LOC measure given their in-depth knowledge of various factors within their jurisdictions affecting the five dimensions. It is therefore unwise to diminish or limit agencies' autonomy for scoring the five dimensions as they understand them. However, when first learning to apply a new tool additional guidance can be useful. Table C.3 contains examples from the Technology Risk Registers to aid new users of the CB-LOC. Table C.3 lists an example of a hazard/technology/goal combination scoring a "4" and a "1" for each of the five dimensions. These examples can serve as upper and lower pegs that agencies can keep in mind while producing their scores.

The intent is for agencies to see which aspects of a hazard are most distinctive and how one may be compared to the other. The objective CB-LOC approach also conveys information that can be applied in managing risk. Results would be used within a corresponding risk matrix (priority "heat map") to allow assessment of relative priority across hazard/technology/goal combinations. Repeating CB-LOC assessments periodically could generate pattern data for the hazard/technology/goal combination over time before data from relevant signpost metrics are available to be collected and analyzed.

To come up with a composite CB-LOC measure across the five different characteristics, the team examined and adopted a set of heuristic rules. They privilege judgments regarding the capacity of an agency to respond to risk and how swiftly they may need to do so as follows:

- If the "Response" and "Velocity" elements are both rated 3 or 4, the CB-LOC measure should be set at an overall value of 4.
- If the "Response" element alone is a 3 or 4, the CB-LOC measure should be set at an overall value of 3.

Table C.3. Examples of scores resulting from applying CB-LOC rating criteria.

Dimension	Score	Examples from the Risk Registers and Reasoning
Novelty	4	**E4: Hacking charging station**—Cybersecurity issues abound; however, the ability to spread malware, conduct data theft, and other malign activities through refueling infrastructure and the electrical grid have not been encountered at a mass scale. Should EVs supplant internal combustion engines, cybersecurity and data privacy risks will be pervasive within a familiar form previously thought to be reasonably secure.
	1	**M4: Discrimination**—Discrimination against protected classes is a problem.
Velocity	4	**E2: Exposure to emissions**—Historically marginalized communities are more exposed to emissions. Current market trends could perpetuate this reality due to EVs and charging infrastructure meeting demand from traditionally favored communities and delaying any benefits from decreased emissions to historically marginalized communities.
	1	**A15: Human error**—Market size for AAM likely limited to a small group while adoption rate remains minimal.
Size (affected)	4	**C12: Air pollution and GHG emissions**—If CAV adoption leads to increased VMT and the vehicles are not zero emission, increased GHG. Emissions could result, jeopardizing agency plans and exacerbating climate change.
	1	**C3: Workforce obsolescence**—Obsolescence of knowledge skills of agency workforce affects a limited population.
Information	4	**C1: Hacked infrastructure**—There have been very few events of hacking autonomous systems and very limited information on the consequences of compromising an interconnected transportation infrastructure-vehicle ecosystem, resulting in a sharply increased venue for attack.
	1	**E11: Fuel tax revenue decline**—Research has been conducted on the potential impacts of declining funding from fuel taxes, and studies of alternative tax schemes exist or are ongoing.
Response	4	**E16: Low EV adoption**—Low EV adoption rates result in GHG reduction goals not being met; agencies forced to adapt organizations and policies to climate change.
	1	**E19: Crime near charging stations**—Long charging time increases targeting by criminals or vandals. Agencies must rely on police, private security, and other partners as law enforcement is out of agency scope.

Note: Examples from Chapters 3 through 6 risk registers are listed using their unique identifier along with a brief description of the hazard/technology/goal combination and the reasoning behind the score.

Source: RAND and Sam Schwartz.

- If the "Response" element is rated 1, the CB-LOC measure should be set at an overall value of 1.
- In all other cases, take the simple average across all five elements of the CB-LOC measure and round down to the nearest whole number but no less than 1.

Considerations of Equity in the CB-LOC Measure

The equity agency goal deserves special mention. DOTs and regional MPOs are inclined to plan around large metro or other major economic centers. This is a natural course to take for most of the goals of concern. However, the issue of equity is one of minority opportunity and the need to redress thinking and planning that heretofore has been performed for the benefit of the largest constituency share of a region. This aspect will be treated more extensively in the discussion of rating the severity of consequences from hazards. But it also enters into the present discussion because one of the elements of the CB-LOC measure is the size of the potentially affected group.

To address this problem, the team used a rule of thumb. If a row in the risk matrix (hazard/technology/goal combination) would otherwise receive a "2" because of the narrowness of the group affected by the consequence, that rating is lifted to a "3" if the consequence stems from existing or prospective urban/rural or socioeconomic divides. Because the purpose of this system is to raise agency cognizance of potential risk stemming from emerging and disruptive technologies, equity issues should raise consideration to the next level even though by strict size measure they would only warrant a "2" on the size dimension.

Harmonizing the Two LOC Measures

Rather than choose between the SI-LOC and CB-LOC measures, both should be present and available to agency risk managers. Both convey value and allow agencies to tailor risk management to regional circumstances at different technology trajectories.

The principal argument against having two such measures is to limit the work necessary for the methodology to be directly usable by agencies. Agency managers do not need cumbersome frameworks that would place a strain on limited resources to respond to risks. There is a potential risk of confusion. Yet, the two approaches are useful at different stages of the technology implementation process. In the early days, the CB-LOC approach will be the only one that can be realistically applied. Later, when data become available and tolerance levels become better understood, the SI-LOC approach will prove useful and should dominate.

Therefore, in the risk register, each row presents only one measure-of-concern result. In most cases, given the prospective nature of the technologies in this report and their sources of risk, this will be the CB-LOC measure. However, in those instances for which time series data allow the construction of illustrative SI-LOC measures, those are reported in those spaces. The reasoning is that SI-LOC measures are more likely to be tailored to local circumstances, will be based on experience with the specific hazard/technology pairing, and are usually directly related to the agency goal potentially placed at risk.

In practice, agencies will need to determine for themselves when the shift from using one measure of concern to the other should occur. The team's intent is to provide agencies with as much information as is available during the dynamic, emergent process of technology adoption and diffusion, to provide it in a readily digestible form, and to create as much space as possible for local decision-making regarding risk management.

The Problem of Multiple Agency Goals

Transportation agencies are the public stewards of a range of societal objectives. Transportation agencies are also limited by budget constraints. They do not have a bottom line that can be used as a means for net assessment of how well they are succeeding. This is in contrast to a private-sector business that may have several different product lines or cost centers. A loss in one may be made up for with a gain in another. Doing well on sustainability does not compensate for any lapses in achieving safety goals or maintaining mobility. This is a challenge for constructing a risk register that accounts for the disparate goals transportation agencies pursue.

The research team approached this problem by framing a qualitative grading system across the agency goals identified in this study. Table C.3 provides an outline of this system. Each column represents either one of the outward-facing agency goals or includes a set of inward-facing goals. Each column is divided into four sections indicating differences in the severity of outcomes in that goal area. The items in cells with a rating of 1 represent the mildest set of goal-specific outcomes while those rating a 4 represent the most severe consequences of goal failure. The entries in each cell provide a representative but by no means a comprehensive list of the degree of severity of items appearing in the consequence column in each row of the risk register.

The purpose of grading the severity of consequences for not achieving agency goals is to provide input into the risk matrix that assigns priorities to each row of the risk register. With the appropriate proxy for likelihood, this information can provide a consistent priority ranking, one of the standard outputs from the construction and operation of a risk register and risk matrix. To make this work, however, one important asymmetry has been added.

To avoid anomalous results, not all goals are fully extended across all four cells representing degree of severity. The most severe category of goal failure, 4, is limited only to consequences that include widespread serious injury or loss of life, catastrophic economic loss, or the introduction of major new inequities into the transportation system. A similar judgment is applied at the other end of the scale. For a goal, such as sustainability, there is a sound argument for making a 1 represent no increase in any of the consequences listed in the lowest cell of that column. In some cases, this might be the standard to apply. But this would run the risk of biasing the scale upward, along with the priority level derived from applying this result into the risk matrix, for only incrementally small measurable changes. Therefore, definitions have been set to make room for very small changes ("little or no increase/decrease . . .") to still meet the norm for purposes of determining severity of outcome.

As with all aspects of the method outlined in this report, the specifics included in Table C.4 and the resulting scaling are intended to be tailored to local circumstances, the trends and events attending the adoption of specific embodiments of emergent technologies, and changing information over time. Each cell of the matrix in Table C.3, and each concept within any cell, could benefit from greater detail and reflection. That is one of the intended purposes of this approach: to engender discussion about risk, loss, and hazard that extends more completely across the various offices within any agency beyond that of the risk managers.

One of the reasons not to delve more deeply into the Table C.4 representation is also that regional characteristics would come into play, aspects that could best be defined and tracked at the agency level. To illustrate the importance of region-specific assessment, consider the consequence of the first item in the risk register for MOD/MaaS: an increase in congestion. Given the nature of the full transportation systems of Los Angeles or New York, the severity of this consequence for the goal of mobility might key out as a "2" or "3." In Europe, with its more transit-oriented modal mix, the severity of consequence associated with this hazard/technology pair might be rated "1" or "2." For communities of fewer than 200,000 people, the rating could be rated as no more than "1." The team's intent is to provide a framework that will enable agencies to take a dynamic approach to risk management processes and to adjust the risk-bearing postures of agencies accordingly.

Risk Matrix Framework

Several sources of risk may be anticipated for each emerging transportation technology. The risk matrix, sometimes referred to as a risk priority heat map, is a tool to aid agencies in prioritizing specific hazard/technology combinations. It is intended to improve determination of how agency resources and efforts should be allocated. The risk matrix takes as inputs the LOC measure score (acting as a stand in for the likelihood that is difficult to estimate in the absence of a certain level of use and experience) and the severity score for the consequence described in any row of the risk register.

The risk matrix has as its rows the levels of severity score and as its columns the LOC score. Each is rated 1 to 4 with a higher number representing greater relative severity of consequences or LOC, respectively. The resulting cells of this matrix then take on values of 1 to 16 (i.e., $1 \times 1 = 1$ to $4 \times 4 = 16$) accordingly. This value is the risk priority score. A breakdown of how the inputs are aggregated to produce an output is shown in Table C.5.

Table C.4. Representative scale for assigning severity of consequence scores across agency goals.

Severity Score	Equity	Safety	Environment and Sustainability	**Mobility** (access and ability to get around in a reasonable amount of time)	Security and Privacy	**Internal Goals** (budget, liability, workforce, acceptance)
4	- Very low access to public and private infrastructure and services for groups made disadvantaged by income, race, ethnicity, gender, age, disability, ethnicity, location (e.g., rural), etc. - Very high disparity in exposure to transportation emissions and adverse health effects.	- Very high fatality and injury rates. -Catastrophic property damage (such as equipment/facility damage, large cargo/package damage) with very high economic cost with indirect loss of life as a result.	Leads to growth in GHG emissions.	- Very low ability for all to get around in a reasonable amount of time. - Access to economic opportunities is limited during most hours; most commuters will have major challenges traveling to desired locations (e.g., 90+min, on average) to access opportunities for a commute.	- Data breaches (e.g., data theft, data destruction) of government (federal or state) sensitive data, national security data, international data. -Security/privacy consequences (e.g., hacking) leading to severe safety impact levels.	—
3	- Low access to public and private infrastructure and services for groups made disadvantaged by income, race, gender, age, disability, ethnicity, location (e.g., rural), etc. - High disparity in exposure to transportation emissions and adverse health effects. -High disparity in exposure to visual and noise pollution.	- High rate of crashes (i.e., high crash-to-VMT ratio). - Serious permanent injuries or health impact possible. -Property damage (such as equipment/facility damage, cargo/package damage) with high economic cost.	- Largely exceeds GHG emissions target. -High increase in energy consumption. -High increase in land use requirement for parking, charging, etc. -High increase in waste stream. -High cost of scaling up. -High operating or maintenance costs.	- High increase in number of ground/aerial transport vehicles driving per hour. - 50% longer trip than off-peak travel times. -Frequent or long operational delays. -High increase in wait times for charging. - Access to economic opportunities is limited during most hours; most commuters will overcome these challenges (e.g., 60+min commute on average) to access opportunity.	- Corporate-level data breaches/cyberattacks, such as propriety information theft, trade secret leaks, malware, etc. -Hijack of individual vehicle/aerial transport. - Data theft of very sensitive PII (e.g., access to bank accounts, credit cards, passwords). -Theft of equipment with high economic cost. -Security/privacy consequence leading to major safety-level impact. -Rideshare physical attack or robbery.	-Recurring budget shortfall. -Shared tort liability (with majority stake). -High shortage of staff with key skills. - Lack of or conflicting regulations.

2	- Moderate access to public and private infrastructure and services for groups made disadvantaged by income, race, gender, age, disability, ethnicity, location (e.g., rural). Affordability: -Higher cost-to-income ratio. - Higher average trip cost per mile. - Medium disparity in exposure to transportation emissions and adverse health effects. -Disparity in exposure to visual and noise pollution.	- Moderate, nonpermanent injuries, requiring short-term treatment. - Moderate increase in crash-to-VMT ratio; moderate increase to crash rate. - Moderate injury rate. -Moderate property damage (such as equipment/facility damage, cargo/package damage) with medium economic cost.	- Moderately exceeds GHG emissions target. -Medium increase in energy consumption. -Increase in visual and noise pollution. -Medium increase in land use requirement for parking, charging, etc. -Shortage of infrastructure or technicians. -Moderate increase in waste stream. -Medium cost of scaling up. -Medium operating or maintenance cost.	- Moderate increase in number of ground/aerial transport vehicles driving per hour. - 20% longer trip than off-peak travel times. -Moderately frequent or moderate operational delays. -Shortage of infrastructure or technicians. -Moderate increase in wait times for charging. - Access to economic opportunities is limited at some times; commuters will overcome (e.g., 45+min commute on average) to access opportunity.	-Unauthorized eavesdropping or photo/video/audio surveillance but no control. -Basic PII data breach (e.g., name, email address, phone number). -Theft of equipment with moderate economic cost. -Security/privacy consequence leading to moderate safety-level impact.	- Minor budget shortfall. - Shared tort liability (with minority stake). - Minor staff insufficiency but high percentage need training. -Insufficient regulation (i.e., regulation exists but is not comprehensive enough).
1	- High access to public and private infrastructure and services for groups made disadvantaged by income, race, gender, age, disability, ethnicity, location (e.g., rural). Affordability: - Slightly higher average trip cost per mile. -Slightly higher cost-to-income ratio. - Low disparity in exposure to transportation emissions and adverse health effects. -Low disparity in exposure to sight and noise pollution.	-Minor illness or injury requiring medical treatment (e.g., first aid). -Minor property damage (e.g., equipment damage, package damage) with low economic cost. - Low crash-to-VMT ratio; low crash rate. - Low injury rate.	- Meets or slightly exceeds GHG emissions target. - No or slight increase in energy consumption. -No or slight visual and noise pollution. -No or slight increase in land use requirement for parking, charging. -No or slight increase in waste stream. - No or slight increase cost of scaling up. -No or slight increase in operating or maintenance cost.	- Low increase in number of ground/aerial transport vehicles driving per hour. - No or only slightly longer trip than off-peak travel times. -Infrequent or only short operational delays. -No or only slight increase in wait times for charging. - Access to economic opportunities is not limited. (e.g., <30 min commute on average) to access opportunity.	-Limited data breach. - Non-PII data theft. -Theft of equipment with low economic cost. -Security/privacy consequence with no safety impact level.	- No or slight budget shortfall. - Minimal tort liability. - Retraining or additional training needed for staff.

Source: RAND and Sam Schwartz.

Table C.5. Risk matrix for assigning risk priority.

		Level of Concern Score (Likelihood Proxy)			
		1	2	3	4
Severity of Consequence Score	4	4 x 1 **4** Moderate	4 x 2 **8** Moderate-High	4 x 3 **12** Extreme	4 x 4 **16** Extreme
	3	3 x 1 **3** Moderate	3 x 2 **6** Moderate-High	3 x 3 **9** High	3 x 4 **12** Extreme
	2	2 x 1 **2** Low	2 x 2 **4** Moderate	2 x 3 **6** Moderate-High	2 x 4 **8** Moderate-High
	1	1 x 1 **1** Low	1 x 2 **2** Low	1 x 3 **3** Moderate	1 x 4 **4** Moderate

Note: Due to the input scores ranging from 1 to 4, there can be no cross product equal to 5, 7, 10, 11, 13, 14, or 15.
Source: RAND and Sam Schwartz.

The product of the two scores is used to classify the total risk of a hazard/technology pair. A hazard/technology combination scoring a 4 in either LOC (column) or severity of consequence score (row) and at least a 3 in the other category (i.e., 3×4 or 4×4) should be cause for the highest level of concern by agency risk managers. These are rated as extreme risk, the highest level of risk priority. Similarly, scoring a 3 in both dimensions (3×3) should receive priority attention just below that of the 3×4 and 4×4 combinations. These entries are rated as high risk priority. Those receiving a product of 6 or 8 are rated medium-high, those totaling 3 or 4 are listed as moderate risk priority, and those with 1 or 2 are rated as low.

The approach reflected in Table C.5 provides a reasonable balance of priority assessments across the various technologies, hazards, and consequences for agency goals encapsulated in the risk registers in Chapters 3 through 6. Appendix A provides the full summary statistics of risk priority results derived from the risk matrix when applied across all items in the risk registers in Chapters 3 through 6.

APPENDIX D

Full-Text Policy Primers

The policy primers in this appendix are a small set of key issues for agencies to better prepare for managing risk arising from emerging and disruptive technologies. This will require maintaining situational awareness and a capacity for foresight. It will also require development and implementation of courses of action designed to be robust to different futures arising from the consequences of newer technological innovations in transportation.

While Chapter 7 provided condensed primers of the selected briefs, this appendix provides fuller discussions of each. Taken together, they are intended to create an organizational consciousness of potential risk that would connect risk management directly with more routine operational and planning activities. The appendix provides an outline of a program for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register across Chapters 3 through 6.

The briefs included in this appendix are shown in Table D.1.

Because the briefs address different topics, the format for each brief may vary. Generally, each brief contains the following information:

- Description of the higher-level policy or strategy.
- Efficacy of the brief or strategy (i.e., how will this help).
- How to apply the policy or strategy, if applicable.
- Stakeholder considerations.
- Potential unintended consequences.
- Hurdles or potential obstacles to the policy or strategy.

Table D.1. High-level policy primers and strategy briefs included in Chapter 7 and Appendix D.

Policy Brief	Topic
1	Ensure Access to Necessary Workforce Skills
2	Monitor for Early Signpost Detection
3	Enhance Cybersecurity, Data Privacy, and Awareness
4	Ensure an Adaptive Culture of Safety to Risks from Emerging Technologies
5	Prepare for Data Sharing, Data Management, and Digital Policy
6	Detect and Examine Implicit Assumptions to Enhance Awareness
7	Create Capacity for Decision-Making under Deep Uncertainty (DMDU) (Nonpredictive) Analytics
8	Strengthen Sensitivity to Equity Implications of Agency Decisions
9	Practice Early Stakeholder and Community Engagement

In some cases, the discussion will be grouped according to the specific technologies analyzed by the research team. In others, the discussion can be stated in more mode-agnostic terms. Where possible, references for further information as well as examples of agency use have been included.

Policy Brief 1: Ensure Access to Necessary Workforce Skills

The purpose of this strategy brief is to raise awareness of measures that could enhance agency ability to manage and mitigate risk related to workforce obsolescence. The brief is intended to create an organizational consciousness of potential risk of insufficient access to necessary workforce skills. Awareness of potential future workforce challenges would connect risk management more directly with more routine operational and planning activities.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. They outline steps for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. Emerging technologies in transportation could bring about economic and social opportunities as well as a host of challenges. One challenge is that those technologies can drive a wide-ranging transition of the workforce both internal and external to the agency. In both cases, this may include creating or eliminating job functions and increasing or reducing the number of jobs. Ensuring access to necessary skills and workforce can support achieving economic and social opportunities. The process starts with understanding the gaps between the current workforce and what is needed in the future. However, emerging technologies by their nature present deep uncertainties about their future adoption and skill requirements. Furthermore, limited access to high-quality new jobs could extend into the future the current economic gaps for populations that have been underserved and made disadvantaged. In addition to this brief, strategies in the following sections on developing and monitoring signposts (Policy Brief 2), DMDU analytics (Policy Brief 7), and sensitivity to equity implications (Policy Brief 8) could help with workforce planning for agencies.

Efficacy: How Will This Help? State and federal transportation agencies deliver infrastructure and services with a host of partners, including private-sector contractors and consultants. Ensuring access to the right skillset and needed workforce, both internally and externally, would help agencies meet their various agency goals and missions. Skills that are common in private industry—such as data science, analytics, and business intelligence—may still be novel in the transportation sector, particularly for smaller, regional transit agencies. Agencies can bridge this gap by enhancing human resource efforts in recruiting, training, retraining, and implementing structured succession.

More broadly, the Infrastructure Investment and Jobs Act (IIJA) provides new opportunities for agencies to address infrastructure needs at the national and local levels (Kane and Mills 2022). This historic investment along with the Inflation Reduction Act could accelerate systemwide improvements in the transportation sector if the right workforce is available and high-quality job opportunities are accessible to everyone. To maximize the IIJA funding benefits, agencies should focus on investing in workforce development (training, upskilling, and reskilling), increasing the diversity of the workforce, and better coordination among agencies and programs.

Agencies also require enhancing their workforce to better meet the emerging needs arising from new transportation technologies. Other high-level strategies that can mitigate risks from emerging technologies are outlined. Those strategies emphasize collaboration and partnership between agencies, industry, affected communities, experts, and stakeholders. Acquiring the right skillsets to implement suggested strategies will mitigate risks posed by emerging technologies. Moreover, skills that are common in private industry—such as data science, analytics, and business intelligence—may still be novel in the transportation sector, particularly for smaller, regional transit agencies. By targeting human resource activities such as recruiting, training, retraining, succession management, and systematically identifying gaps in core competencies, agencies can ensure that their workforce stays relevant.

How to Apply the Strategy or Policy in Practice. Forward-looking policies that can ensure a skilled and prepared future workforce may include early identification of trends in skills that may become in demand along with wider adoption of emerging transportation technologies, investment into workforce training and development, retraining programs for workers in the sectors displaced by emerging technologies, and equitable workforce considerations.

The skills gap in the U.S. labor market has been an area of interest for academics, corporations, and government agencies alike; transportation agencies are no exception. Agencies need to assess current and emerging skills gaps, retrain internal staff, hire outside experts, and create partnerships that can complement skills that agencies do not possess. An example of a near-ubiquitous need for cybersecurity workforce preparedness would, at a minimum, require agencies to develop self-assessment capabilities—and, ideally, have systems, processes, and staff equipped with the skills necessary to detect, prevent, and mitigate cyber-related vulnerabilities.

The following are several trends stemming from emerging and disruptive technologies that bear watching.

EVs and MOD/MaaS

- The rise of the sharing economy has disrupted traditional economic models, as private individuals commercialize previously private-use assets such as cars. The EV sector in the United States saw a tenfold increase in annual sales and the number of models produced in the first 5 years since 2011. The sector is projected to grow at a cumulative annual growth rate of ~25% over the next 5 years (Fortune Business Insights 2022). Subsequently, EV charging infrastructure will have to grow by 20% per year until 2025 to meet projected demand (Nicholas et al. 2019). This would mean more demand for skilled labor for safe and efficient deployment, and a prepared workforce to meet agency goals around mobility and sustainability.
- As EV and MOD/MaaS technologies diffuse and become more accessible, transit agencies may find themselves competing with private firms to attract a diverse, inclusive, educated, and appropriately trained workforce.

CAVs and AAM

- Workforce training will be needed to create a talent pool of next-generation mechanics, manufacturing, supply chain, air traffic controllers, and electrical/software engineers to fulfill demand for future skills.
- Some workforce-related challenges might be too novel to adequately prepare in advance, given numerous uncertainties in the adoption pathways these technologies take. Industry leaders and staff can facilitate the development of essential skills, such as computer literacy and advanced mechanical/electrical abilities, by engaging and cultivating interest in these areas among high-school and college students to establish a broad and skilled talent pool.

Stakeholder Considerations. It is clear from both the scale and extent of potential workforce transition and dislocations that this is a consideration for more than just transportation agencies. Whether addressing the internal agency requirements, the external requirements necessary for others to ensure safe and efficient operation of changing transportation modes, or the need to balance opportunity of access to evolving or newly emerging job descriptions, a level of stakeholder engagement and active partnership among government levels and with the private sector will be required.

As an example, in addition to EVs and MOD/MaaS affecting employment by demanding a larger share of the workforce equipped with unique skillsets, these emerging technologies also disrupt workforce practices. MOD/MaaS often relies on gig workers (part-time, flexible schedule, independent contractors) who are less likely to have benefits and living wages (Shaheen et al. 2020). The COVID-19 pandemic has driven many workers to the gig economy. While most transit agency employees are unionized and have protected worker rights, TNC drivers are often considered contract workers with little influence on their employment conditions.

The hiring practices of MOD/MaaS providers, specifically the classification of workers as independent contractors, can affect employee compensation, taxes, and benefits, and is one of the primary concerns of relevant federal and state stakeholders (Shaheen et al. 2020). Furthermore, some studies have revealed that these drivers may be making less than minimum wage per hour due to fees, fares, and payment structures from service providers (e.g., drivers are not paid for the time they spend on the app without a customer, or for the time it takes to travel to a waiting customer—"deadheading") (Scheiber 2020).

More research on the fair compensation of TNC drivers is needed because available studies draw different conclusions.

Costs, Benefits, and Equity in Distribution of Costs and Benefits

While shared mobility and the transition to clean energy vehicles have increased employment opportunities, they have also contributed to downward wage pressures (when considering hourly wages, app fees, contractor status, and worker benefits). Further regulation may be needed to protect workers' rights and limit risks of (1) lack of a trained workforce and (2) worker exploitation. The hiring practices of MOD/MaaS providers, specifically the classification of workers as independent contractors, influence employee compensation, taxes, and benefits.

There are also opportunities to close gaps in employment opportunities, particularly civil or construction-related jobs for communities that have been made disadvantaged. For example, in 2021, the FTA announced an initiative, implemented as a pilot program, to permit transit agencies to use hiring preferences on FTA-funded construction projects to promote equitable creation of employment opportunities and workforce development activities. The initiative has transitioned in response to the BIL, which includes hiring preferences related to the use of labor for transportation construction projects (FTA 2022).

Labor trends specific to MOD/MaaS could include more demand for positions such as data scientists or personnel that rebalance/recharge micromobility devices, or the need for retraining of existing staff (Shaheen et al. 2020). This is a risk because public agencies especially may lack the human or technical resources to accommodate and oversee MOD/MaaS operations and initiatives (e.g., analyzing big data generated by mobility providers) (Shaheen et al. 2020).

Literature on the skills gap in the United States also highlights the opportunities gap that researchers have recently brought into focus (Goger and Jackson 2020). The narrative of a motivated person plus skills equaling success assumes that we exist in a neutral, level market that affords all people equal opportunity. However, in practice, this is not the case.

Establishing workforce development programs can connect low-income residents and youth to emerging mobility-related job opportunities. Additionally, establishing local hire requirements targeting underserved communities may create transferable skills among low-income neighborhoods and improve overall local labor market participation rates.

Potential Unintended Consequences. Planning for workforce development and transition could have many challenges. There is a risk of over- or underestimation of labor force and skills due to the uncertain adoption rates and technological development. The distribution of opportunities may not be equitable. Several strategies are presented that can be employed to mitigate the planning to some extent.

There are some jobs at risk of being displaced by emerging transportation technologies (e.g., mechanics, drivers). Without a just transition plan, affected jobs and workers could suffer unduly in this process.

Hurdles and Potential Obstacles to Policy or Strategy. The risk of lacking access to the skill and workforce is compounded as a result of the high rates of retirement as the baby boomer generation leaves the workforce; increasing need for reliable and efficient transportation by travelers and shippers, new workforce methods, materials, and technologies; and an expanding array of emerging issues across environmental, administrative, and technical domains (*Special Report 275* 2003).

As mentioned previously, lack of information, uncertainties on technology adoption speed and scale, and internal agency capacity to plan and mitigate workforce-related risks are potential obstacles.

Examples of Specific Actions in This Group

- Metropolitan Transportation Authority (MTA) New York City Transit offers a paid transit electrical apprentice and transit mechanical apprentice program through the New York State Registered Apprenticeship Program (U.S. Department of Labor n.d.). MTA also works with a high school dedicated entirely to transit career training.
- In 2021, the Minnesota Department of Transportation conducted a SWOT (strengths, weaknesses, opportunities, and threats) and SCOPE (Situation, Core Competencies, Obstacles, Prospects & Expectations) analysis to evaluate future workforce needs through anonymous employee surveys (Bartlett et al. 2021).
- The State of Ohio is reducing its workforce-related risks by proactively implementing remote tower infrastructure at selected airports in Ohio based on FAA criteria and establishing partnerships with Kent State University for worker retraining (Del Rosario et al. 2021).

Policy Brief 2: Monitor for Early Signpost Detection

The purpose of this strategy brief is to raise awareness of measures that could enhance the agency ability to manage and mitigate risk through earlier identification and monitoring of possible indicators (signposts) of changes that place agency goals at risk. The brief is intended to create an organizational consciousness of the need to be aware of important trends and developments. Awareness of early indicators of emerging risks would connect risk management more directly with more routine operational and planning activities.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. The steps are outlined for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. Signposts are early indicators or warnings of a potential hazard. For transportation agency risk management, they are predetermined indicators that a foreseeable hazard may have arisen as a result of transportation technology deployment. In the language of scenarios, often used when planning for an uncertain future, they are signals of how the future may be trending and so affect the plausibility of different scenarios for the future. It will be valuable for DOTs and MPOs to monitor signposts and such signal indicators as part of a risk management strategy for emerging and disruptive technologies.

Chapters 3 through 6 provide a landscape of the potential risks and hazards facing MPOs and DOTs as emerging mobility technologies gain momentum. Each row of the risk register has at least one suggested signpost, an indicator based on the listed source of risk to agency goals, that is intended to stand as a harbinger for the listed hazard.

Efficacy: How Will This Help? The strategy of thinking in terms of signposts—data- or observation-based early warning indicators of potential emerging risks—applies across the full range of sources of risk (hazards) found in the rows of the risk register. It is not limited to being associated with any one of the major agency goals nor limited to technology type. Rather, it is geared to enhancing transportation agency risk management capabilities generally and may be applied broadly across the full azimuth of potential risks from emerging and disruptive technologies. The concept is a useful habit to inculcate into agency processes and deliberations.

While the risk sources and associated signpost indicators in Chapters 3 through 6 are intended to be a starting point for DOTs and MPOs to consider how to monitor vulnerability to emerging hazards, agencies can also perform a gap analysis to identify other signposts. The development of signpost indicators may be allied to the process of making assumptions explicit as discussed in the brief on detecting and examining implicit assumptions (Policy Brief 6).

How to Apply the Strategy or Policy in Practice. Rather than beginning by examining existing data series to select signpost indicators, it will serve agencies better to consider how a hazard and consequence pairing could affect the agency's ability to meet its short- and long-term goals or its mission. To help agencies identify signposts, they should consider the following question: "What would be the best proxy for conveying an early warning sign of an emerging risk?" Only then should there be an assessment of what data are available, where gaps exist, and how the appropriate signpost can be framed for future tracking as the technology's implementation goes forward.

The process of framing a signpost indicator would also need to consider a baseline target level the agency will set and that will become the reference for trends. Also, establishing tolerance levels above and below these targets would help determine if a measured result for the indicator is within or out of tolerance of the target. Validating the baseline and tolerance levels would require an assessment of available literature, (i.e., the degree to which information is available and how much agreement there is among contributions to the literature). Finally, periodic assessments of the signpost indicator would be advisable to ensure the chosen metric is effective in indicating to the agency the degree to which goals can be met.

Almost all the entries in the risk register were written with the intention that transportation agencies would work from that starting point and then tailor elements to the specifics of their regional setting and circumstances. This is especially the case with the suggested signposts. Agencies should determine the appropriateness for their region of each signpost in the risk register. Regions may not need to monitor every signpost in this report. Likewise, some communities may consider adding or subtracting items from the suggested list of signposts. Discussions to determine which risk sources are of greatest concern will need to occur.

If the signpost is deemed appropriate for a region, stakeholders should then discuss what would be the measured level above (or below) which concern would arise that the hazard is manifesting itself. This calibration process will need to be set on a regional basis. For example, there may be different levels that would trigger concern about greater congestion resulting from MOD in different regions based on geographic or infrastructure constraints.

Stakeholder Considerations. Through the process of developing and prioritizing signposts, agency decision-makers would benefit in several ways from having active engagement with community members from a diversity of backgrounds. Their perceptions and concerns will guide the selection of early warning signposts of risk to agency goals and community interests. Such engagement can range from active listening sessions to more inclusive measures. DMDU methods, referred to and briefly discussed in Policy Brief 7, lend themselves to a deliberation process supported by an analysis that can facilitate an inclusive decision-making process. This can help agencies achieve community-facing goals as well as develop a robust understanding of the challenges facing their region and the hazards their community may be most sensitive to.

Costs, Benefits, and Equity in Distribution of Costs and Benefits

A potential opportunity cost relates to the extent to which technology diffusion takes place—diffusion of technology would need to be sufficiently underway to generate the data required for monitoring signpost indicators. This shortcoming highlights the need for this report's CB-LOC measure for proxying likelihood before a deployment point sufficient to generate those data.

By not putting in place a strategy to monitor signposts, an agency's ability to fulfill its goals, an agency may be faced with larger barriers along the timeline of implementation.

Benefits of monitoring the trends of SI-LOC include early awareness of and potential for timely response to indications of unmet agency goals, especially those on equity and responsiveness to historically underserved communities. Monitoring changes to the CB-LOC could produce similar benefits in the absence of data-driven signpost indicators that would support calculating the SI-LOC measure (see Appendix C).

Potential Unintended Consequences. As with any indicator selected to provide insight into underlying, hidden, or complexly interrelated processes, there are several possible risks. Any single indicator is susceptible to either false positives (a risk is emerging that is less consequential than it seems) or false negatives (all appears to be well, however, risk is growing).

This possibility can arise from the selection of that indicator to the exclusion of other potential signposts, flaws in the design of the indicator, problems with acquiring data of sufficient quantity and quality, and potential errors in interpretation. Some of these issues may be reduced by working not with one signpost indicator but with a dashboard of several. This increases the resource costs involved initially and continuously. Further, the more signposts, the less value in any one such indicator.

Employing a systematic approach to the weighing and selection of signposts through some of the methods discussed can alleviate this potential for error as can eliciting a wide assortment of inputs through stakeholder involvement. As with any set of indicators, the best guard against false readings would be to periodically review the value of the information received and match results to ongoing monitoring efforts.

There are two approaches that could reduce some of the institutional or personal biases that might come into play when nominating and interpreting the data connected with signposts. One is to broaden the diversity of representation in the process of developing signposts. This would mean engaging other divisions within the transportation agency, including those involved with daily operations. It could also mean reaching out to other agencies, possessors of expertise, and potentially affected communities. The other approach to reducing unintended bias is to assign to other internal or external actors the task of monitoring specific signposts once established.

Within a transportation agency, the work units, other than the risk management team, that are associated with a particular hazard could be tasked with monitoring and assessment.

Hurdles and Potential Obstacles to Policy or Strategy. Identifying relevant data and the availability of such data will be challenging for agencies monitoring for early signpost detection. Even in today's environment, many regional agencies have a limited workforce with the skillsets needed to analyze the enormous amounts of data these emerging mobility technologies are likely to produce.

While it is appropriate to determine signposts for each source of risk in the risk register, the necessary data collection behind each indicator will lag behind the deployment of the technology. At present, EVs and MOD/MaaS are more likely to have a data time series to draw on for some hazards because these technologies are already in use across the country. On the other hand, because CAVs and AAM are further out on the horizon, and there is more uncertainty about the availability of data to monitor potential signposts.

As knowledge of emerging mobility technologies evolves, so can their signposts. Recurring discussions to determine what risks and their associated hazards are most important to an agency and region should take place.

Owner(s) of Policy or Strategy. Transportation agency planners and their risk managers.

Range and Timeframe of Effectiveness. Signposts may be established as soon as planners have identified a potential hazard/source of risk that may emerge from an implemented or prospective technology. Gap analysis comparing the identified signpost indicator to available data sources could affect both signpost choice and future monitoring. Collection and analysis of selected signpost data may only be available once diffusion of the technology is underway.

Policy Brief 3: Enhance Cybersecurity, Data Privacy, and Awareness

The purpose of the following strategy brief is to raise awareness of measures that could enhance an agency's ability to manage and mitigate risk related to cybersecurity and privacy.

The intent is to create an outline of a program for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. New transportation technologies are moving toward an always-connected, data-collecting norm. U.S. DOT has issued guidance to "[s]trengthen transportation system resilience to protect it from disruption from cyber and other attacks" and to "[h]arden U.S. DOT's enterprise information and communications technology against cyberthreats." (U.S. DOT 2022a). At the same time, the U.S. DOT, state DOTs, and MPOs are seeking to "[d]evelop and manage data systems and tools to provide objective, reliable, timely, and accessible data to support decision-making, transparency, and accountability" (U.S. DOT 2022a).

Though there are specific agency goals aimed at protecting cybersecurity and data privacy, emerging and disruptive technologies may blur the lines of categorical risk. The connected nature expected of new transportation modes envisions vehicles interacting with other vehicles, personal mobile devices, transportation infrastructure, and communications and payment networks. This implies avenues of attack available to hackers and others that have not existed before.

Ensuring cybersecurity and protecting data privacy while also leveraging these data for informed decision-making pose unique challenges to transportation agencies as they expand beyond their traditional purviews. The introduction of V2V or V2I communications creates vectors vulnerable to infiltration and can result in outcomes affecting both the physical and information space. Vehicle control systems may be accessible to remote operators by design or automated by traditional or advanced machine-learning algorithms. In either case, they offer a method by which outside observers may intercept communications between subsystems and insert their data to manipulate vehicle maneuvers thereby putting passengers and the public in danger. Some technologies will only be able to offer services if allowed access to PII. In other cases, users may not be aware of what data are being collected and shared, thereby opening the door to privacy concerns and creating targets for large-scale data breaches associated with identity theft. Finally, because payment systems are connected to the Internet, emerging technologies, like EVs and EVSE, have already been targeted by hackers.

Efficacy: How Will This Help? It is crucial for a transportation system to ensure that system data and privacy are secure and to implement measures of mitigation when security cannot be guaranteed. Doing so would mean more effective protection of data and privacy (e.g., terms of use, PII, financial information, geotagging), making certain of the security of new mobility technologies and securing infrastructure against various forms of denial of use or other types of attacks with mass effects, security of EVSE and other supporting equipment.

How to Apply the Strategy or Policy in Practice. Mitigation strategies will need to be resilient in the face of changing infrastructure, increasingly interconnected data streams, and a quickening pace of technology adoption. To prevent or mitigate risks, there are three cybersecurity objectives to meet in a cyberphysical system: (1) availability of the service, (2) integrity of the data and data exchange, and (3) confidentiality of the data transmissions (Gottumukkala et al. 2019). The following strategies can aid practitioners in pursuing and achieving these objectives.

Strict Data Access Standards. Across the data lifecycle (i.e., creation, storage, usage, and sharing), access to data from internal and external actors needs to be well-regulated to ensure privacy and protection of sensitive data like PII. Coordination among agencies and with outside partners exposes data to vectors of attack. Widespread data security standards and regulations for the handling and management of sensitive data will reduce potential threats to consumers of emerging technologies and the public.

Detection Algorithms. A critical component of risk mitigation against cybersecurity is detection of an attack. By instituting detection algorithms, false data insertion, "man-in-the-middle," and denial-of-service attacks could be more quickly responded to, and their consequences limited (Bhusal et al. 2021). Targeted vehicles like EVs/CAVs, AAM aircraft, and the infrastructure and systems that support these mobility options would need to develop detection algorithms. Industry would also need to follow any standards set forth by government entities like FAA, NHTSA, SAE, and NIST (Gottumukkala et al. 2019). Detection algorithms will not lower the exposure of infrastructure and vehicles to cyberattacks, but they can help reduce the scale of a hazard's impacts and the length of time those impacts are endured.

Cybersecurity Testing. An effective way to ensure robust infrastructure is to perform cybersecurity testing and assessments during installation (Bhusal et al. 2021). Private industry and third parties will be essential partners in ensuring that systems are up to date at the time of installation and will receive updates regularly. This should also include data QA checks.

Raising Cybersecurity Awareness. State DOTs and MPOs in consultation with federal agencies such as CISA can jointly work to develop and implement employee training and exercises to ensure agency personnel are aware of cyberphysical risks and potential infrastructure vulnerabilities. Over time, there has been an evolution in the preferred methods of training delivery for DOT employees, although there is still a strong preference for print/electronic materials. Conferences, peer exchanges, and web-based seminars on cyber-related threats may increase awareness and reduce the risk of interconnected cyberphysical threats. Similarly, participation in cybersecurity awareness activities such as those provided by CISA can help identify potential vulnerabilities before they manifest as serious threats.

Creating Clear Terms of Use Agreements. Where private, for-profit providers use personal information for their commercial needs and interests or sell personal data to a third party, there exists the potential for consumers to be unaware of the amount of data they are sharing and with whom. To combat this, robust data interoperability standards, cloud storage of user information, and protocols for data access can reduce user exposure to cyberthreats and highlight early warning signs before a major data breach.

People often do not understand what information they are consenting to share or are unaware of the private information being disclosed due to the use of opaque user agreements. Developing clear protocols to protect system security and customer privacy is integral to the adoption of these emerging technologies. Along these lines, creating clear terms for data privacy in private provider agreements is an important regulatory measure that will support clean information sharing between providers.

Stakeholder Considerations. Because data ownership and user privacy are concerns that are likely to evolve and become more at risk as more user information (as drivers, owners, passengers, renters) is stored, accessed, and moved over multiple channels, measures for risk assessment governing user data should evolve in tandem. While most cybersecurity protections look for bold and brash attacks, most successful cyberattacks have been found to be subtle and relatively well hidden. Data interoperability standards, cloud storage of user information, and protocols for data access should be continually updated in line with the latest industry practices.

While this area of concern and practice is vital to transportation agencies, it is also clear that the sources of risk, consequences, and solutions extend beyond the purview of such government organizations. What the agencies need to do is to move this to a high level of priority for risk management and avail themselves of opportunities to work with other agencies, vendors, and NGOs to remain on the cutting edge of cybersecurity.

Costs, Benefits, and Equity in Distribution of Costs and Benefits

The costs of not taking an active posture toward cybersecurity and data privacy would seem to outweigh those of doing so. It is possible that raising these concerns could affect acceptance by the public and therefore retard the adoption of what might otherwise be technologies that could help achieve agency goals. However, it is more likely that large-scale breaches leading to loss of privacy, loss of system security, and other effects are more likely to give potential users pause before adoption. Data privacy and data thefts and breaches should therefore be thought of as potential costs if actions are not taken to develop strategies early on for data sharing.

Any data sharing, even for enhancing cybersecurity and protection, carries with it certain inherent risks. On the other hand, inadequate data sharing and collaboration may result in information asymmetry. Without ample data and information sharing, MOD/MaaS providers or those creating SAV services may have more information on travel patterns than DOTs and transit agencies. This could lead to loss of effectiveness by agencies in operations, planning, and regulation. Private-sector entities may be concerned that sharing and storage of data could have potential impacts on proprietary trade secrets. “The Federal government determines that private companies control the data AVs generate, reinforcing a business model based on data sales and consumer loyalty. Companies grant free rides in exchange for data (and travel routes that take customers past certain stores)" (National Association of City Transportation Officials 2019, 20).

Potential Unintended Consequences. Because of the balance of differing interests, the potential severity of risk owing to information flow will likely vary due to factors such as compliance, data security standards, and regulations governing the handling and management of sensitive data.

If incorrectly controlled and stored, data points can be combined to form PII from several more innocuous-seeming data sources (National Association of City Transportation Officials 2019, 76). Data blurring or other anonymization methods could protect community identities and privacy.

Hacking of CAV, EVs, AAM, or any other innovative technologies could be a significant unintended consequence of information gathering and information sharing. Most often, cyber-attacks tend to be acts of espionage rather than sabotage. Such information-gathering activities may portend future acts of sabotage and may also serve as early warning signals for a future, more coordinated attack.

If "[g]overnments fail to define journey data (e.g., "breadcrumb" route information, starts/stops) as [PII] or to enact comprehensive data protection legislation . . . companies and governments alike [could] acquire unprecedented access to the private actions and movements of citizens" (National Association of City Transportation Officials 2019, 20).

Hurdles and Potential Obstacles to Policy or Strategy. For EVs, protocols and standards are still in development. Best practices for ensuring cybersecurity for charging information are still being developed. There are also limited services available to perform cybersecurity-related testing and assessment, for example, at charging stations and for EVs, as well as for end-to-end communications between EVs, EVSE, and the power grid. Cybersecurity for wireless charging infrastructures is still in the testing and demonstration phase (Bhusal et al. 2021).

Beyond this, DOTs and MPOs will need to collaborate with the federal government, vendors, and other stakeholders to see passage of comprehensive legislation for strong cybersecurity standards for vehicles, to hold manufacturers accountable for breaches, but also to determine their roles in the ecosystem providing cybersecurity and personal privacy (National Association of City Transportation Officials 2019, 37).

Owner(s) of Policy or Strategy. State DOTs, MPOs, private-sector vendors and service providers, and various agencies of the federal government beyond the U.S. DOT.

Range and Timeframe of Effectiveness. The need is already present and growing. If history is any guide, there will be a continuous arms race between nefarious actors and regulators throughout the growth and adoption of emerging transportation technologies. Further, with each new technology development come new opportunities for system failure, resulting in a need for early and continuous attention.

Policy Brief 4: Ensure an Adaptive Culture of Safety to Risks from Emerging Technologies

The purpose of this strategy brief is to raise awareness of measures that could enhance an agency's ability to manage and mitigate risk related to hazards to safety stemming from adoption of emerging and disruptive mobility technologies. The brief is intended to create an organizational consciousness of potential risk of insufficient attention to agency safety goals. Continuing the commitment to safety to the forefront in all transportation agency processes connects risk management more directly with routine operational and planning activities.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. The steps are outlined for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. Ensuring the transportation ecosystem of the future is safe for all mobility consumers, and industry personnel requires a safety-first approach in decision-making and work processes. DOTs and MPOs should use this safety-first approach (1) to ensure the safe operations of the transportation system (Vision Zero framework) and (2) to ensure that vehicles are manufactured and can operate safely.

In recent years, there has been a movement toward thinking about the safe movement of people over the rapid movement of vehicles. Transportation providers around the world have begun to acknowledge that even one death from a transportation system is unacceptable. To fix this, providers have begun to focus on creating spaces that allow for the safe mobility of all road user types. This practice is known as Vision Zero, and it relies on a Safe System Approach to infrastructure planning. The Safe System Approach is "founded on the principle that humans make mistakes and that human bodies have limited ability to tolerate crash impacts. . . . Applying the Safe System Approach involves anticipating human mistakes by designing and managing road infrastructure to keep the risk of a mistake low; and when a mistake leads to a crash, the impact on the human body does not result in a fatality or serious injury" (FHWA 2022). When faced with hazards from transportation technologies that have the potential to increase traffic-related injuries and deaths, a culture of safety built into agency infrastructure planning decisions at all levels becomes imperative. Furthermore, the ability of the Safe System Approach to expand, adapt, and evolve beyond its original envisioned scope becomes a key component to making certain that agencies continue on the road to Vision Zero even when confronted with the vast changes that emerging mobility technologies may bring.

Beyond this, transportation agencies have also been encouraged to shift internally toward a culture of safety. If Vision Zero is a strategy to eliminate all traffic fatalities and serious injuries, then that safe systems concept refers to an intentional approach to achieving Vision Zero. A safety culture, as defined by the U.S. DOT, is the shared values, actions, and behaviors that demonstrate a commitment to safety over competing goals and demands (FHWA Office of Safety 2019).

A culture of safety exists within a transportation agency when ". . . [t]he organization proactively elevates road safety as a priority . . . and makes a commitment to integrate safety in all aspects of transportation programs and projects. Employees have safety in mind when planning, scoping, designing, and constructing a road. Employees regularly communicate the importance of road safety with colleagues, customers, and contractors. Executive leaders are vocal supporters of safety and empower employees to seek innovative approaches to improving safety even if safety is not explicitly part of everyone's job title" (FHWA 2020).

In addition to taking a safe systems approach when making transportation system infrastructure improvements, transportation agencies will need to create training and workforce standards that ensure the safe manufacturing and operations of emerging technologies. For example, as EVs become increasingly widespread, improved training and updating emergency response guides to include incidents not previously considered (e.g., high-voltage lithium-ion battery fires in EVs) are critical to ensuring first responders are adequately prepared and competent during emergencies (NTSB 2018). Workforce training and the development of early warning notification systems that monitor for hardware and software vulnerabilities can also help agencies detect and respond to potential data breaches and safety and security threats.

Efficacy: How Will This Help? The following subsections contain information for EVs and MOD/MaaS and for CAVs and AAM.

EVs and MOD/MaaS

With MOD/MaaS giving commuters increased access to shared micromobility with devices like bikes and scooters, a larger share of commuters may be considered vulnerable roadway users. By raising awareness of and prioritizing safety goals, DOTs and MPOs prioritize creating infrastructure solutions that cater to all road user types including vehicles, micromobility users, pedestrians, children, older adults, and those with disabilities. This will lead to a safer mobility ecosystem for all. While Vision Zero's Safe System Approach is well known for tackling unsafe components of the transportation infrastructure, another pillar highlighted by FHWA is creating safe road users. DOTs may play a role in creating safe road users by designing driver regulations that promote safe driving habits. Regulations, for example, to keep drivers from staying behind the wheel for dangerous amounts of time without proper rest while working as MOD service providers, may keep commuters from being at heightened safety risk.

New technologies, particularly EVs, pose novel mechanical challenges such as risk of battery fire and explosion. Increased regulatory oversight rooted in a culture of safety can ensure proper response to electrical shocks and fires caused by EVs. DOTs can also develop regulations to promote workplace organization, reducing fall and trip hazards that threaten workers during installation and maintenance of EVSE. Additional elements that ensure manufacturers are manufacturing safe vehicles to "minimize the occurrence and severity of collisions" using the latest vehicle technologies may also give DOTs added confidence that all stakeholders are actively involved in creating a safe mobility ecosystem for all (FHWA 2022c).

CAVs and AAM

With the introduction of CAVs and AAM, digital infrastructure (in addition to physical infrastructure) has become increasingly important in promoting a safe transportation system. State DOTs and MPOs will need to ensure there is real-time mapping that replicates the human environment by seeking passage of regulations that require this. There will also need to be a workforce with the skillset to oversee mapping by OEMs. Further, conscious efforts to integrate real-time mapping into higher-level planning decisions now will help agencies prepare adequately and "future proof" regions, enabling mobility technologies to operate seamlessly and intermix with other modes.

With CAVs and AAM aircraft being earlier in the development stages, they present many uncertainties that may affect community and worker safety. MPOs and DOTs can prepare for this more uncertain future by working with industry leaders to allow for standard operational requirements, airspace integration (for AAM), automation, and electric charging (Del Rosario et al. 2021).

Stakeholder Considerations. The following subsections contain information for EVs and MOD/MaaS and CAVs and AAM.

EVs and MOD/MaaS

Infrastructural change allowing a region to progress toward the Vision Zero goal can require large investments. While there is more certainty around the consequences of EV and MOD/MaaS adoption than the more prospective mobilities delivered by CAVs and AAM, developing infrastructure strategies that are multiuse, flexible, and modular may allow regions to respond to how emerging technologies will change what it means to respond with a safe system approach. Communication with industry partners and third parties responsible for testing EVs and other emerging mobility technologies will help MPOs and DOTs highlight areas for digital and physical infrastructure improvements earlier in the adoption phases.

Ensuring the safe manufacturing and operation of emerging mobility technologies will also require that MPOs and DOTs develop plans with educational institutions to prepare a workforce for evolving needs. Labor trends specific to MOD/MaaS could include more demand for positions such as data scientists or personnel that rebalance/recharge micromobility devices, or the need for retraining of existing staff (Shaheen et al. 2020). Training will be critical to ensure agencies can safely and adequately respond to these hazards. While most transit agency employees are unionized and have protected worker rights, TNC drivers are often considered contract workers with little influence on their employment conditions. The hiring practices of MOD/MaaS providers, specifically the classification of workers as independent contractors, can reduce employee compensation, taxes, and benefits as well as the safe operation of the platform.

CAV and AAM

As CAVs become commonplace, they will need to be accounted for in transportation modeling and forecasting tools to better account for outcomes CAVs will have on the transportation supply, road capacity, and travel demands over the long term (Zmud et al. 2018; Blas et al. 2022). Long-range planners should begin to discuss how to integrate CAV adoption curves in modeling exercises. On top of this, CAV deployment will affect public revenue. Restructuring property and fuel taxes should be considered so that regions can continue investing in Vision Zero infrastructure (see discussion in Appendix B, Policy Brief 4). As AAM matures, agencies and stakeholders may need to implement or refine policies and procedures to mitigate risks associated with cybersecurity, ground crew interference, passenger interference, and terrorism, for example.

Thoughtful approaches to the operations of CAVs and AAM will ensure that personal safety and cybersecurity are top of mind during the decision-making process. Updating current maintenance practices by incorporating connected infrastructure elements such as asset management lists for roadside units (RSUs) can reduce cyberthreats. Given the nonuniform distribution of current CV deployment across the United States, state DOTs and MPOs can also benefit from sharing best practices and lessons learned to continuously improve transportation asset management practices (U.S. DOT 2021 and 2022). QA checks can highlight threats before they evolve into systemwide cybersecurity incidents. This could be done by strengthening existing IT infrastructure departments and risk assessment processes or introducing more robust data handling practices.

Equity of Distribution of Costs and Benefits. If agencies and other stakeholders do not act with transparency, collaboration, and equity at the forefront of Vision Zero efforts, there will likely be unintended, inequitable outcomes that disproportionately affect communities of color, low-income communities, people with disabilities, and other groups that have been made disadvantaged.

EVs and MOD/MaaS

A Vision Zero commitment necessitates a proactive approach to developing transportation infrastructure. Regions should prioritize "self-enforcing roadway designs and policies" that "lessen the need for reactive enforcement measures" (Shaum 2022). With this approach, regions can work toward a system that exposes individuals less to transportation injuries and preventable injustices (e.g., racialized traffic stops) (Shaum 2022). However, digital infrastructure will become increasingly important as mobility technologies evolve. For example, building charging infrastructure that is secure against cybersecurity threats could make it less accessible to individuals without membership or those without a credit card. Developing systems to ensure equitable access to these emerging technologies will require innovation, collaboration, and transparency at all steps of the planning and decision-making process.

Although MOD/MaaS shared mobility services have increased employment opportunities, there is still work to be done to ensure these employment opportunities provide safe work environments. MOD/MaaS have led to downward wage pressures and present risks of worker exploitation. To prevent this, actors should develop workforce training programs that train workers on the unique protocols necessary for maintaining emerging mobility technologies and developing workforce standards of operation and pathways to good and promising jobs (Shaheen et al. 2020).

CAVs and AAM

The introduction and proliferation of CAVs could lead to additional VMT and congestion if proper regulations are not in place to limit unoccupied vehicles from cruising. A component of creating a safe transportation system will be creating digital and physical infrastructure but also the regulation to limit unwarranted cruising. Without regulation, CAVs may cruise or park in a city's—often lower-income—outer-ring neighborhoods, creating more opportunities for collisions, injuries, and congestion in these communities.

Potential Unintended Consequences. A commitment to Vision Zero will require a commitment to developing holistic infrastructure investments that create safe environments for all road users. As technologies and the ways people move through urban environments evolve, infrastructure solutions that promote a safe system will likely change, too. Evolving transportation patterns may lead to evolving infrastructure needs. Adaptive infrastructure solutions may allow regions to be resilient when facing these patterns of change, but they may also lead to an overall increase in infrastructure expenditure.

Incorporating safety into all decision-making processes during CAV adoption could lead to "significant safety gains for people taking transit, walking, biking, rolling, and driving" (National Association of City Transportation Officials 2019, 12). These safety gains will only be made, however, if federal and state governments authorize AVs to operate on public streets after "developing objective and verifiable safety performance standards and tests that ensure automated driving prevents injury collisions and fatalities among all right-of-way users" (National Association of City Transportation Officials 2019, 20). If this approach is not taken, the result will be the creation of new risks and hazards.

Hurdles and Potential Obstacles to Policy or Strategy. Currently, TNCs and other mobility companies are not required to share their data with local governments, making it difficult for agencies to make policy updates that utilize up-to-date data from mobility providers. Creating requirements for data sharing will likely be the first obstacle to overcome to create effective policies that tackle the right topics. Analysis of these datasets will highlight where safety-based policy improvements are needed. As the National Association of City Transportation Officials states, "Cities need the power to set contextually appropriate limits and gather information about new modes, especially at a time when the market is rapidly changing and agreed-on conventions are not yet set" (National Association of City Transportation Officials 2019, 26).

Today, there is significant uncertainty around the potential consequences and adoption timeline for CAV and AAM. Challenges to predicting the impact of CAVs and AAM deployment could reduce an agency's ability to plan long-term infrastructure investment needs. In addition, CAVs and AAM will likely require unforeseen investments in both physical and digital infrastructure, straining regional transportation budgets and capacities. Infrastructure planning and development timelines may not match if regions experience rapid adoption of CAVs or AAM. Another challenge in AAM adoption is public perception. Even if decision-makers take a safety-first approach, public perception may still be a barrier to individual user adoption. Hesitance and concerns over community impacts, equity, and safety of AAM may persist.

Owner(s) of Policy or Strategy. MPO and DOT leadership and long-range transportation planners/modelers.

Range and Timeframe of Effectiveness. Taking a safety-first approach in transportation planning should happen as early as possible. Even if adoption timelines are on the 10–20-year time horizon, it is not too early to begin working toward a Vision Zero goal.

Policy Brief 5: Evaluate Data Sharing, Data Management, and Digital Policy

The purpose of this strategy brief is to raise awareness of measures that could enhance an agency's ability to engage in safe data sharing and data management that will accompany the increasing adoption of emerging and disruptive mobility technologies. The issues arise as key concerns for the ability of agencies to manage and mitigate major sources of risk. The brief is intended to create an organizational consciousness of the potential risk of insufficient attention to data-sharing issues. Commitment to safe data and digital practices and protocols in all transportation agency processes connects risk management more directly with routine operational and planning activities.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. The steps are outlined for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. The sharing of data among service providers, institutions, and public agencies can increase understanding of the consequences of innovative emerging transportation technologies for travel behavior, equity, and the environment. Data can broadly be divided into three types: (1) open data, (2) proprietary data, and (3) personal data. **Open data** are data that are publicly available for download or through application programming interfaces (APIs). These data may require a subscription or other fee. **Proprietary data** are data related to the company or corporation including copyright, patent, or trademarked material (e.g., proprietary code). Proprietary data can also be important to a company's business plan or growth strategy. In contrast, **personal data** include email addresses, phone numbers, and other personally identifiable data (PII). Personal travel behavior (e.g., origins and destinations) and Internet protocol (IP) addresses (to the extent that they can identify a particular individual or location) also constitute personal data. Protecting all three types of data, while still enabling information sharing with other mobility and information services, is a continual challenge and potential risk.

Efficacy: How Will This Help? Industrywide security standards, data-sharing practices, and common computer languages may assist in addressing common challenges. Some guiding principles for data sharing and management include:

- **Establish Data Standards.** Determine the type of data useful for public-agency and private-sector use for the planning, design, operation, safety, and maintenance of the transportation network as well as the development of third-party apps. Determine the format and standards for publishing datasets that are consistent with industry standards, other public entities, and address interoperability issues. Develop standards for aggregating these data and disseminating the aggregated data in real time. Develop standards for classifying and updating data and include metadata with key methodological information on how data were collected. Requiring geocoding location-based data can make such data suitable for mapping functions.

- **Create Data Management Policies.** Establish standard operating procedures to protect consumer privacy and proprietary data. The establishment of user agreements for those sharing and receiving data can aid in data management.
- **Establish Conditions for Use.** Require transportation service providers and apps to share data as a condition for offering services within a jurisdiction. Require that data sources filter and scrub their data, according to set standards, before sharing their data.
- **Develop Data Accessibility Standards.** Ensure that data made available are in an open format that can be downloaded, indexed, searchable, and machine-readable to allow automated processing. Alternatively, or in addition, it is possible to engineer software collection systems that are data-format neutral.
- **Consider Open License Policies.** Ensure that aggregated and anonymized data are available to the public for use and that policies articulate prohibited data uses.
- **Ensure Data Quality and Timeliness.** Ensure data are high-quality scrubbed for plug-and-play end use by developers without requiring extensive effort to make datasets usable. Data should also be made available as quickly as possible and frequently enough to remain current and usable.

Stakeholder Considerations and Applying Strategy in Practice. The following pertain to emerging data standards, emerging regulations, and data governance.

- **Emerging Data Standards.** Governed by cities, the Open Mobility Foundation (OMF) brings together public- and private-sector stakeholders to develop and promote technology used by commercial mobility service providers and government offices that manage the public right-of-way. OMF is an open-source foundation that creates a governance structure around open-source mobility tools, such as Mobility Data Specification (MDS). MDS is a data and API standard that allows service providers and public agencies to communicate with each other about their services because it consists of two APIs: a service-provider API and a public-agency API. In doing so, MDS allows public agencies to gather, analyze, and compare real-time and historical data from mobility service providers and serves as a measurement tool that helps enable the enforcement of local regulations. MDS has the potential to enable public agencies at all levels of government to operationalize digital infrastructure and leverage it dynamically to manage mobility policy and public rights-of-way such as curb space and potentially airspace management.

  In addition to MDS, several public and private entities have come together to establish mode-specific data standards. One of the earliest standards is General Transit Feed Specification (GTFS) (formerly known as Google Transit Feed Specification). GTFS defines a common format for sharing public transit information and can include static information (e.g., timetables), real time (e.g., location of a bus or train), and flex (e.g., additional capabilities for demand-responsive services). Additionally, the North American Bike Share Association adopted an open data standard, known as the General Bikeshare Feed Specification (GBFS) to make real-time bikesharing operational data feeds publicly available in a standardized format. GBFS does not include historical usage data or other PII.
- **Emerging Regulations and Data Governance.** Concerns over user data privacy have led to important developments in privacy laws that could affect open data sharing. The EU's GDPR, which became effective in May 2018, establishes a set of standards for how companies handle EU citizens' data to protect consumer and personal data. Key requirements of GDPR include requiring the consent of subjects for data processing, anonymizing collected data to protect privacy, providing data breach notifications, safely handling the transfer of data across borders, and requiring certain companies to appoint a data protection officer to oversee compliance. GDPR applies to any company that markets goods or services to EU residents, regardless of its base location. In 2020, California implemented the California Consumer Privacy Act, which sets forward similar requirements to GDPR. California's law classifies geolocation data

as personal information. In addition, consumers can request to know what data are collected about them and how these are collected as well as ask for personal information to be deleted by the business. Even in the absence of specific legislation and regulation, public agencies can take a proactive approach to developing their internal practices and policies for data sharing, data management, and privacy protection.

Hurdles and Potential Obstacles to Policy or Strategy. Despite the value in pooling or sharing data, there can be concerns about what data are shared, how the data are shared, who sees the data, and what the data are used for. Data sharing may pose challenges regarding traveler privacy, protecting trade secrets, public records requirements, data security, institutional capacity, and the lack of universal data management standards. Table D.2 summarizes many of these concerns and potential strategies for mitigating each concern.

Table D.2. Potential concerns with data sharing and potential strategies for addressing them.

Issue	Potential Concern	Potential Strategies
Protecting Traveler Privacy	Mobility services or apps may intentionally or unintentionally collect sensitive and PII.	Require the removal of PII before sharing data. Aggregate data to protect traveler information. Require opt-in consent processes for data sharing.
Protecting Trade Secrets	Mobility services or apps may generate or rely on proprietary information that can be important to an organization's unique business plan or growth strategy.	Use third-party organizations as data brokers (i.e., intermediaries). Reserve the right to share data for public interest reasons. Engage in data-sharing agreements that define what type(s) of data will be shared.
Abiding by Public Records Laws	Data used by public agencies may be subject to public records requests which can potentially reveal traveler or proprietary information.	Treat location-based data as PII. Develop unique protocols for proprietary data. Allow only select reported data to be made publicly available.
Data Security	Data shared between agencies and organizations may present security risks (e.g., security breaches, data theft).	Adopt standards-based digital security methods (e.g., storage protocols, data theft plans). Ensure security policies and practices are regularly evaluated and updated if necessary. Encourage organizations to adhere to the best practices of data security.
Staff Capability Constraints	Stakeholder organizations may not have the staff capability to handle the safe sharing and storage of data.	Develop new positions (e.g., chief technology officer) to maintain in-house capabilities. Coordinate across organizations to establish best practices.
Lack of Universal Standards	Data may be generated in a nonuniform way which can complicate data sharing.	Partner with outside organizations to adopt standardized data formats. Promote open and standardized data formats. Collaboratively develop format-neutral data collection protocols and algorithms.

Source: RAND and Sam Schwartz.

Policy Brief 6: Detect and Examine Implicit Assumptions to Enhance Awareness

The purpose of this strategy brief is to raise awareness of measures that could enhance an agency's ability to recognize important underlying assumptions that should be made explicit to better manage and mitigate risk stemming from adoption of emerging and disruptive mobility technologies. The brief is intended to create an organizational consciousness of the importance of these assumptions for reducing potential risk and creating an overall posture of resilience toward risks from new technology. This is also a key element for creating robust plans of action that may perform well under a variety of future scenarios. Identifying and interrogating underlying assumptions in all transportation agency processes connects risk management more directly with routine operational and planning activities.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. The steps are outlined for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. Risk management is an aspect of transportation agency planning. All plans are forced to make assumptions about the future. Some of these assumptions are explicitly identified and planned for (e.g., "We assume a future real interest rate of 3% during the coming period.") Nevertheless, most plans also contain implicit or hidden assumptions. Most of these are innocuous (e.g., that the legislature will continue to meet as scheduled to consider revenue bills) but some of them can lead to substantial divergences between what was presumed to be a prudent risk management posture and the reality that it confronts in the future (e.g., "In our plan we have accounted for existing modes of last-mile transportation. Wait a minute: Are those TNC rental scooters? Where did they come from?!").

Implicit or unconsidered assumptions can be a source of significant risk management strategy failure. This may be especially true if the assumption, explicit or implicit, that turns out to be vulnerable is a key assumption underlying a risk management posture. A partial means for offsetting these effects is to adopt a stance of risk aversion and a generally conservative posture toward change. However, transportation agencies are unlikely to be the principal drivers for implementation and wide adoption of transportation technologies. Other forces will be in play. Therefore, another element of preparing for a resilient posture toward the risks posed by emerging and disruptive technologies would be to gain insight into where hidden assumptions may lie so that they may be explicitly accounted for in risk management strategies.

Assumptions are woven into planning because of the uncertainty involved. Uncertainty in the realm of emerging technology is not a failure of due diligence; rather, it is inherent in looking toward the long term. It is specifically intrinsic to the enterprise of new technology innovation and diffusion. That, along with its tendency to displace incumbents and create new relationships, is what makes technology disruptive. In the presence of systemic uncertainty, it becomes crucial to systematically identify key explicit and implicit assumptions to ensure that they are part of the planning process.

Efficacy: How Will This Help? The strategy of enhancing agency awareness by identifying implicit assumptions in technology risk management planning applies across the full range of hazards/sources of risk found in the rows of the risk registers in Chapters 3 through 6. It is not limited to being associated with any one of the major agency goals nor limited to technology type. Rather, it is geared to enhancing transportation agency risk management capabilities generally and being applied broadly across the full azimuth of potential risks from emerging and disruptive technologies.

Amid dynamic change arising from the deployment of emerging and disruptive technologies, static approaches to risk management can provide a useful baseline. But they can also prove to be a trap due to a misplaced perception of concreteness. It is almost certain that the scale or direction of change, the hazards and consequences that emerge, and the implications for plans and operations will be beyond the bounds of any static system to foresee or manage. Rather, agencies will be well served to establish a posture of resilience toward this category of risk. Part of this will require inculcating a planning culture of thinking in terms of alternative assumptions. This will be a key to framing less brittle, more robust risk management planning. Identifying and weighing assumptions that may be key to specific strategies or policies but also possibly vulnerable under certain plausible future states of the world is a valuable tool. With this capacity, not only can transportation agencies frame more robust risk management postures, but it opens the possibility for considering hedging actions against possible broken assumptions or shaping actions to help guide the unfolding implementation of new technologies into trajectories that will reduce the challenges faced by the main risk management plan.

How to Apply the Strategy or Policy in Practice. The method of ABP is focused on the discovery and characterization of explicit and implicit assumptions (Dewar 2002). It is intended as a tool for reducing avoidable surprises that could disrupt plans. Originally intended as a means for double-checking draft plans, it could also be applied earlier in the plan development process.

Assumption-Based Planning (Dewar 2002) provides several methods for identifying implicit assumptions. The concern is greatest for those assumptions that might be load-bearing (that is, intrinsic to the success of a plan) and vulnerable to challenging future scenarios. Dewar provides several practical means for making hidden assumptions explicit and finding those that are key to a risk management plan. We briefly present three that are readily applicable to transportation agency risk management:

Rip Van Winkle. You have been asleep for ten years and are then asked to state how well the agency has been able to manage risks ensuing from the four—now prevalent—transportation technologies. Before answering, you can ask and receive Yes/No answers to ten questions of the character of "Did the incidence of cyberthreats increase over the past ten years?" The discipline of determining what questions are the most important and most likely to provide clues to how the deployment unfolded from the perspective of limiting risk to agency goals is the heart of the exercise—especially when you are limited only to ten. Comparing the questions that emerge to the present risk management plan should provide insight into what assumptions may be vulnerable. This technique may be used with a group of people across several rounds. After the first round, each of the participants received a full exposition of which question the others raised in their replies. Then the group is polled once more—or several times—with the full set of answers in each successive round made available for all to consider for the next round.

Backcasting. This method would begin by positing a failure in an aspect of the agency's risk management plan for emerging technologies. This can be done by focusing on the range of individual hazards in successive iterations, selected hazards of greatest concern, or a set of related hazards as a whole. Participants are then asked to explain what went wrong: What was the nature of the failure? What happened to cause the failure? What did not happen that then subsequently led to the agency confronting excessive risk or deleterious consequences? This exercise can be performed asynchronously with a wide circle of participants and then be reviewed by the planners to infer the vulnerable assumptions in the risk management posture of the agency.

Strategic Assumption Surfacing and Testing (SAST). The methods used for eliciting and assessing key assumptions may be selected as much by ability to fit within agency culture or the size and nature of the planning team or stakeholder community as by any intrinsic criteria associated with the method. SAST is a loose description of a graphical approach to eliciting and characterizing assumptions that might be more suitable in some situations. It can be used in a Delphi-like manner to go through successive asynchronous rounds of elicitation.

Participants representing diverse views and backgrounds are arranged in several groups whose members share some common interests or responsibilities. Each either develops or is assigned a policy course or strategy to address the central issue of concern (e.g., safety, mobility). Each group proposing a strategy then identifies the assumptions underlying their preferred course of action. They arrange these assumptions in a 2 × 2 table with two axes: (1) importance of the assumption to the preferred strategy and (2) degree of certainty or uncertainty surrounding that assumption. They also identify the key, load-bearing assumptions.

The results can form the basis for one or more workshops as the views of each group are aired and discussed. Or, one of several methods may be used to go through several virtual rounds similar to a Delphi study.

SAST, along with the other two methods (as well as others of a more technical nature) found in Dewar (2002), can be used to identify load-bearing assumptions that may either be buried implicitly in agency risk management plans or are explicitly recognized. They serve as entrees to a whole-of-agency approach to considering the key, load-bearing, explicit, or implicit assumptions.

Consciously employing such exercises to review risk management imparts a changed state of mind or frame of reference for those involved with such planning. Not all exigencies can be reduced to a universally applicable plan. There will be surprises that confront even the most meticulously detailed strategy. But the habit of thinking in terms of detecting assumptions, determining the degree of their load-bearing relevance to the agency's goals, and considering potential consequences for the agency missions and stewardship of societal objectives will serve to enhance the resilience of agency staff and units in the face of the uncertainties presented by disruptive novel technologies.

Stakeholder Considerations. Detecting and evaluating assumptions involves internal agency activities as well as outreach to other government bodies, communities, or stakeholder groups. Any product that might issue from such a deliberative process may be of value to agency risk management and planning. However, the process outcomes may prove equally valuable for the connections made and channels of communication opened through stakeholder involvement.

Costs, Benefits, and Equity in Distribution of Costs and Benefits

Active efforts to discover and assess implicit assumptions can be beneficial to enhance risk management effectiveness. The issue of equity may be one of the most telling instances of its potential to enhance agency approaches to risk. There is a tendency in planning to employ aggregates, averages, and comparisons of before-and-after states of welfare in managing change. However, aggregates (such as change in gross domestic product) do not guarantee that all included will benefit equally or that some will not be harmed. Means and medians may mask effects that fall most heavily on a few socioeconomic deciles. Comparing initial states with later-stage or final states does not address the question of how the time path may affect different groups along the way.

A risk register is not a sufficient guide for assigning agency priorities in risk management in all cases. Issues of equity in the distribution of burdens are likely to be underspecified. The size of the group potentially affected enters into calculating which hazards and risks should receive priority attention. One of the reasons that equity issues emerge is that the smaller group is swept into the larger aggregate whose benefits and costs are weighed. There needs to be a conscious effort to avoid the assumptions that lead to this error that can lead to misspecified policies for risk management. The question is how can this consciousness be achieved as part of agency process and practice?

The issue of equity can become the occasion for explicit discussion of assumptions: Are there hidden assumptions about how well all communities and groups might be affected by emerging and disruptive technologies? Are mitigation plans sufficiently cognizant of potential adverse outcomes? The practice of fully comprehending all underlying assumptions, particularly those regarding underrepresented or frequently excluded stakeholders, may be one of the most valuable measures agencies could employ to prevent falling into the trap of assuming what is true for the whole will be true for all groups involved.

Potential Unintended Consequences. As with any technique or process seeking to bring concreteness to an inherently uncertain process, there is always the danger of that concreteness being misunderstood as a guarantee against surprise. While the habit of searching out and assessing underlying assumptions will be of value during planning phases, it would be good practice to review the premises of earlier assessments on an annual basis. This will take advantage of new information that has become available or of different personnel involved in planning for those aspects of operations that can carry excessive risk because of changes in underlying assumptions.

Hurdles and Potential Obstacles to Policy or Strategy. There may be resistance to incorporating new approaches. This may be the case for those activities that are most central to the planning functions of the agency and the modeling and analyses that support them. However, employing new techniques in risk management and using new methods to enhance the means for agency personnel to perceive potential sources of risk early on are likely to be welcomed.

Owner(s) of Policy or Strategy. Transportation agency risk managers and planners.

Range and Timeframe of Effectiveness. Determining and analyzing underlying assumptions will be valuable when agencies engage in processes related to risk management. Further, this approach will be useful in gaining greater awareness of the equity implications of measures that may have been decided on based on the presumed benefits to the widest segment of the population or utilizers of transportation modes. It would be valuable to review assumptions on an annual basis, when new information becomes available, or when the agency risk managers can engage additional expertise and community input.

Policy Brief 7: Create Capacity for DMDU (Nonpredictive) Analytics

The purpose of this strategy brief is to provide an overview of measures that could enhance an agency's ability to analyze and plan more effectively despite an increase in transportation system uncertainty inherent in the adoption of emerging and disruptive mobility technologies. The brief is intended to suggest opportunities to shift from analyses in support of decision-making that are less rooted in prediction to those that allow agencies to explore alternative strategies and policies that might prove robust (i.e., meet preset criteria for good outcomes) across a range of possible future scenarios. This will aid in creating an organizational consciousness for solution-based approaches to reducing potential risk and creating an overall posture of resilience toward risks from new technology.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. The steps are outlined for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. The core problem underlying the management of risk stemming from emerging and disruptive technologies is that of uncertainty. This presents a problem for agencies accustomed to using probabilistic means and forecasting models to support decisions.

Transportation agencies are mandated to produce a series of regular planning documents and have in place an analytical apparatus for doing so. Despite being updated every 4 to 5 years, the pace and scale of today's change render this planning output increasingly less useful for agency strategic guidance. A growing problem is that traditional methods and tools used by agencies are based on predicting future values for important transportation trends and outcomes. Both the pace and scale of today's changes mean forecasts have become increasingly unreliable. The result is that the planning process produces documents that might receive diminishing credence from the public and fail to serve the needs for strategic guidance. New tools that have been developed and applied in other areas, such as DMDU methods, are beginning to be adopted by DOTs and MPOs to address perceived shortcomings in the strategic dimension of transportation planning.

DMDU methods are varied in their format and consist of both qualitative and quantitative model-based approaches. They are designed to examine the implications of different assumptions about the future. The quantitative methods, such as RDM may generate hundreds or hundreds of thousands of simulations that provide a database for systematic examination of consequences. Analytical tools in agencies such as transportation demand models, however, very often take several days of calculation to perform a single run. It may be that some adoption of DMDU methods could allow planners and those charged with agency risk management to have means for bringing more analytical support to their efforts.

Efficacy: How Will This Help? Transportation agencies sometimes employ probabilistic forecasts to suggest which futures are more likely than others. But under deep uncertainty—the condition in which parties to a decision do not know or cannot agree on either the likelihood of alternative futures or on the underlying relationships (models) that link actions to consequences—such forecasts represent yet another assumption, this time regarding the unknown underlying probabilities (Lempert et al. 2003; Marchau et al. 2019). Instead of characterizing uncertainties in such terms (with probabilities being difficult to convey to broad audiences under even the most favorable conditions), DMDU methods characterize uncertainties in terms of the specific problem itself: "Which assumptions would I need to believe to recommend one course of short-term actions over another?" This is most valuable when such probabilistic forecasts are unreliable. As such, DMDU is also designed to support a participatory process called "deliberation with analysis," which can help agencies implement the types of stakeholder engagement they need to improve their plans, build legitimacy, gain buy-in with the public, and satisfy federal requirements for stakeholder participation.

Traditional planning methods, designed to use travel demand models to provide reliable future demand forecasts in "predict-then-act" optimization can foster overconfidence or limit consideration of strategic alternatives or the effects of a wider set of plausible future conditions. Planners and modelers might arrive at myopic decisions because they underestimate the uncertainty. Predict-then-act analyses can lead to gridlock when stakeholders contest the assumptions used to justify a proposed plan rather than work together to identify a plan that performs well over a wide range of scenarios.

How to Apply the Strategy or Policy in Practice. The initial uses in transportation are not to supplant large travel demand models. Rather, DMDU tools have been used to shed greater light and support a strategic perspective within the agency that is difficult to achieve solely with long run-time demand models.

These new DMDU approaches are significantly different from traditional, predict-then-act analysis. DMDU methods begin with proposing an agency plan, stress testing the plan over hundreds to thousands of plausible futures, using these stress tests to generate policy-relevant scenarios that illuminate the strengths and weaknesses of proposed plans, and then using this information to make robust and flexible strategies that perform better over a wide range of futures. Often these plans are designed to be adaptive over time in response to new information.

As discussed previously, ABP could be of assistance to risk managers in applying the methodology used in this report. It would illuminate how best to establish signpost indicators along with their targets and tolerances to create the SI-LOC likelihood proxy (see Appendix C).

ABP was used to support the Road to Zero coalition to frame an agreed-upon roadmap for achieving zero U.S. road fatalities in 2050 (Ecola et al. 2018). It was also used in a community process in Culver City, California, to mediate transportation alternatives between the Culver City Transportation Department, residents, and business owners (Lempert et al. 2020a). Neither application was applied by an agency directly, but both illustrate the possibilities.

RDM uses models and simulations to discover potentially stressful scenarios around which signpost indicators could be framed. Several software packages are available to support agencies using model-based DMDU, including TMIP-EMAT and VisionEval, both of which have been supported by FHWA. TMIP-EMAT is built on a general engine for conducting RDM analysis but also contains an emulator that allows a limited number of runs from a full-scale, long-running travel demand model to be interpreted as a much more rapid response surface (Milkovits et al. 2019; Lemp et al. 2021). In this way, a broad range of possible future conditions can be explored much more rapidly than would otherwise be possible. This allows for the discovery of systematic failure modes and stressful scenarios for intended agency risk management actions.

In an organized 2019 beta test, the Greater Buffalo Niagara Regional Transportation Council (GBNRTC), the Oregon Department of Transportation (ODOT), and the San Diego Association of Governments (SANDAG) conducted tests of the system and compared results (Milkovits et al. 2019). GBNRTC evaluated policy and investment uncertainties associated with improvements along a corridor using as their core model a four-step travel demand model. ODOT examined the uncertain impacts of new technologies and trends using a new activity-based model. SANDAG evaluated policy and investment uncertainties associated with travel demand from Mexico across the border to San Diego using an activity-based model. These beta testers linked their core travel demand models to TMIP-EMAT, generated meta-models, created databases with 5,000 cases, generated scatter plots and other graphs, and conducted scenario discovery analyses. The MPOs reported it initially took about 100 to 400 hours of labor to achieve a running system. Subsequent iterations with new problem framings took about 40 to 80 hours.

VisionEval, on the other hand, is designed to be a fast-running simulation model for explorations at the strategic level but with considerable detail (Miller et al. 2022; VisionEval Organization n.d.). This, too, could be used to answer questions related to the CB-LOC. Using VisionEval, it should be possible to determine what patterns and velocity of technology adoptions would be sources of risk for goals such as GHG reductions.

Several agencies have started implementing VisionEval into their strategic planning, such as Virginia Department of Transportation (VDOT) (Miller et al. 2022), Massachusetts Metropolitan Area Planning Council (MAPC) (Gately and Reardon 2021), ODOT (Wang et al. 2018), and New York State Department of Transportation (NYSDOT) in collaboration with the Capital District Transportation Committee and the Ithaca-Tompkins County Transportation Council

(Resource Systems Group 2019). These implementation efforts have a wide range of objectives, including exploring scenarios of interest (VDOT), forecasting impacts from behavioral changes post-COVID-19 (MAPC), testing feasibility of use in existing planning workflows (NYSDOT), and setting GHG reduction targets at the state and MPO levels and monitoring progress over time (ODOT).

Stakeholder Considerations. Moving away from prediction may sound daunting, but DMDU methods may help agencies operate more effectively in the face of hard-to-predict deep uncertainty. This includes systematic discovery and testing of strategies broadly characterized as having low regret across many plausible futures, designing strategies to flexibly evolve in response to new information, and identifying hedging and shaping actions (based on preidentified signpost indicators to give early warning of how the future is unfolding) to minimize potential loss or help make desired futures more likely.

While this may satisfy several external stakeholder constituencies because of the scope DMDU methods may provide for wider engagement and involvement in transportation planning and regulation, some internal stakeholders may use traditional planning and analysis methods. Rather than starting afresh, DMDU methods can build on the best of agencies' current scenario planning and probabilistic forecasting models. Such models, however, are used differently. Rather than generate predictive scenarios to ask, "What will happen in the future?", DMDU uses exploratory scenarios to ask, "What might happen by varying model assumptions?" and normative scenarios to ask, "How can we best reach our goals despite the prevailing uncertainties?"

Hurdles and Potential Obstacles to Policy or Strategy. Several approaches could ease the introduction of DMDU into agencies' existing processes, protocols, and working relationships:

- Identify, cultivate, and empower local champions for the change within the agency.
- Engage with and work for buy- in from those asked to carry out the strategic foresight efforts and the analyses that will support them.
- Reconceptualize the work process to either elicit the newly looked-for capability or prevent an early rejection reaction.
- Communicate the nature of the intended change to all along the value creation process.
- Think through in advance where potential turf issues might lie.
- Explore how DMDU may play a role similar to that of a smaller, ranging telescope fixed to the side of the main instrument, in this case, the large-scale transportation demand model.
- Apply DMDU methods at the beginning of the planning process. It could be used as a way to bring modelers, analysts, planners, managers, and decision-makers on board at the beginning to frame a conversation and use shared vocabulary that may persist during the cycle even if the DMDU outputs do not form a formal deliverable as part of the planning documents produced.
- Consider early joint exposure to DMDU methods and tools between agency planning and government regulatory agency staff to expand awareness of what might be possible and the utility of the type of output that agencies could produce.
- Seek support from (or at least acceptance by) other partners outside the agency, including federal, state, and local government bodies.

In addition to these general points, the following agency-specific questions illuminate how a team within an agency wishing to explore the use of DMDU tools could proceed most effectively:

- What application areas can provide early and convincing "wins"?
- What methods and tools can be most useful for early adoption?
- What would constitute a good learning path for staff and units looking to innovate?
- What can be done to develop external and internal allies?
- What assistance would be helpful to receive from outside?

Owner(s) of Policy or Strategy. Transportation agency risk managers and planners.

Range and Timeframe of Effectiveness. This effort, too, would reward early preparation, particularly in preparing the ground for the introduction of new methodologies that will likely have the greatest effect once in place and accepted as a regular process within the agency organization.

Policy Brief 8: Strengthen Sensitivity to Equity Implications of Agency Decisions

The purpose of this strategy brief is to raise awareness of measures that could enhance an agency's ability to recognize risk to ensure equitable access to transportation opportunities and an equitable distribution of costs and benefits across communities stemming from adoption of emerging and disruptive mobility technologies. The brief is intended to create an organizational consciousness for making equity an equal concern when balancing risks and creating an overall posture of resilience toward risks from new technology. DOT and MPO leadership should be supported in identifying and developing strategies to address the risk that emerging technology may present equity challenges if not dealt with early on and continuously throughout the technology's adoption. Raising this awareness in all transportation agency processes connects risk management more directly with routine operational and planning activities.

The strategy briefs are intended to help agencies achieve an active posture toward dynamically changing risks. The steps are outlined for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. DOTs and regional MPOs are inclined to plan for large metro or other major economic centers. This is a natural course to take for most of the goals of concern. However, the issue of equity is one of minority opportunity and the need to redress thinking and planning that has been performed for the benefit of the largest constituency share within a region.

Historically, transportation investments have also disproportionately affected negatively communities that have been made more vulnerable—whether unintentionally or not. Today, decision-makers seek a more equitable approach when guiding transportation investments and emerging mobility technologies to ensure that these investments and technologies provide opportunity across the socioeconomic spectrum and do not prove disproportionately burdensome to any group (U.S. DOT 2022d). Because each of the four emerging mobility technologies discussed in this policy brief has varying degrees of uncertainty of adoption and consequence, agencies may need to have different postures or act differently to ensure the equitable distribution of costs and benefits from emerging mobility technologies.

U.S. DOT provides four guiding strategic objectives: (1) expand access, (2) wealth creation, (3) power of community, and (4) proactive intervention, planning, and capacity building (U.S. DOT 2022d). While this definition provides a good starting point for DOTs and MPOs to work with, agencies must have in-depth and iterative conversations about what equity in transportation means for the region at hand. These conversations should engage community members at all stages through implementation and adoption.

With policies like the BIL and others that put equity at the forefront of the decision-making process, state agencies can rewrite the historical trend of inequitable transportation investment. With equity implications engrained, low-income and other communities, including historically underserved communities, older adults, and physically or intellectually disabled individuals, can benefit from the next generation of urban mobility, which seeks to decrease the transportation cost burden, reduce environmental exposure to transportation emissions, and make investments into the clean job pipeline, among others.

Efficacy: How Will This Help? Integrating equity considerations into every step of the decision-making process will ensure that the benefits of an EV future are felt by all. Across the world and specifically in the United States, regions are beginning to end the sale of ICE-powered vehicles (by 2025 in Norway and 2035 in California). DOTs and MPOs must begin to utilize an equity-based framework to develop government subsidies—for both vehicles and charging infrastructure—to support EV adoption for commuters across the economic spectrum.

The accessibility and affordability of MOD/MaaS also pose equity concerns. This is a key issue, especially for TNC and for-hire vehicle (FHV) services that are unaffordable for large segments of the population and have been patronized by largely affluent populations. Studies have shown, for example, that MOD/MaaS users tend to be composed of millennials and Generation Z individuals as well as highly educated individuals and high-income earners (Khatun and Saphores 2022). MOD/MaaS equity challenges include (1) possible discrimination against protected classes; (2) lack of accessibility for older adults and people with disabilities; (3) cost of MOD/MaaS (economic accessibility); (4) digital poverty; and (5) the urban and rural divide (Shaheen et al. 2017b).

While CAVs are currently not available, it is assumed these vehicles will enter the luxury market first and will, therefore, not be affordable to moderate- and low-income users. Once widely introduced, if CAVs are too expensive for household purchase, they will be shared among commuters; however, if prices are affordable to most households, they will likely be used similarly to single-occupancy vehicles—posing equity challenges similar to those communities have experienced from the use of automobiles.

CAV introduction, monitored and guided by MPOs and DOTs, could ensure that CAVs increase equitable access to opportunities and help a region meet its social, economic, and environmental goals. To allow access to all populations, government subsidies may be needed to lower the cost or cost of use of CAVs. Additionally, DOTs and MPOs can also incentivize SAV deployment. This may also reduce the congestion levels brought by CAVs. Demonstrating to the public how the agency is considering safety aspects of CAVs, collaborating with federal agencies, and building public trust, acceptance, and confidence through transparent testing and deployment can also help ensure broad consumer acceptance (U.S. DOT, NHTSA n.d.).

How to Apply the Strategy or Policy in Practice. On the vehicle adoption side, government subsidies must lower the economic burden of EVs for low-income communities by reducing the up-front cost of purchase. (Beginning in 2024, the Inflation Reduction Act allows transferring the EV tax credit to the dealer at point of sale. It also establishes a credit for used EVs.) On the infrastructure side, to make certain that all communities have accessibility to EV charging infrastructure, state DOTs and MPOs should work with legislative and environmental agencies to create incentives and other programs that incorporate equity into their design. Creating a streamlined process for hosting EV charging infrastructure can also help expedite the equitable distribution of this valuable infrastructure, especially in communities made disadvantaged (Wissell et al. 2022).

Taking an equity-based approach to electrifying freight may lead an agency to identify where large freight corridors overlap with historically overburdened communities and areas with a high pollution burden so that agencies can prioritize investments in zero-emission freight. This process will ensure that GHG emissions are not localized in a particular geographic area and are a critical component of fighting for environmental justice.

The introduction of CAVs can also be smoother by agency action: "to ensure equitable service coverage, cities can choose to regulate or incentivize." As a regulator, cities should explicitly identify equity as a policy goal when approving new or expanded services and provide all operators clear, measurable outcomes (e.g., percent of rides taken by riders who have been made disadvantaged, percent of rides originating or ending in a low-income neighborhood) that must be met or exceeded (ARCADIS 2017, 21).

An equity-based approach to decision-making on MOD/MaaS can put regulations in place to ensure that infrastructure projects will put in place a platform that can accommodate physical, cognitive, auditory, visual, and other disabilities to expand MOD/MaaS's reach. Internet access, a smartphone, and banking services are essential prerequisites for utilizing MOD/MaaS (Shaheen et al. 2017b).

Partnerships between transit agencies and micromobility providers could make MOD/MaaS more attractive to lower-income communities if appropriate and competitive pricing mechanisms are in place and if micromobility hubs are securely located in minority neighborhoods (Khatun and Saphores 2022). MOD/MaaS affordability programs can subsidize the cost of operation and enhance access to people of all income levels. Pilot programs in Chicago (Divvy for Everyone) and Los Angeles (Universal Basic Mobility Pilot) show promise to make MOD/MaaS affordable (Carpenter 2022).

While there is significant uncertainty about the level of adoption of AAM, developing training programs that prepare populations made disadvantaged for AAM jobs would provide stability and upward mobility to these communities that have been made vulnerable. Similar to the other technologies, creating affordable fare programs could play an important role in expanding the affordability of AAM.

Stakeholder Considerations. Equitable solutions may differ from one location to another based on how the region defines equity and its social, economic, and geographic constraints. Regions should define their stakeholder list based on this flexible definition of equity. Stakeholders should also be aware that pilot programs may allow a community to test numerous potential solutions and provide additional transportation options, particularly to low-income communities. In the Bay Area, for example, the Metropolitan Planning Commission and TransForm have designed mobility hubs with electric carsharing and charging stations in low-income communities. "The Goal is to increase access for low-income residents to economic opportunities, medical facilities, schools, parks, and grocery stores while reducing vehicle trips and GHG emissions" (California Department of Transportation 2022, 68).

The fact that starting prices have increased for BEVs even while battery costs have decreased should serve as a reminder to agencies of the importance of developing equitable EV policies, subsidies, and incentive programs. Along these lines, there are also a very limited number of nonluxury-brand EVs. Because of this, subsidies may need to be more significant until there are more economical options available on the market. More than just the amount of the rebate should be considered. Further targeted subsidies (eligibility qualifications for additional rebates based on income or local air quality level) and other incentives may be delivered at point-of-sale to make EVs more affordable.

On the goods movement side of transportation and due to historical zoning patterns and decisions that led to the creation of the federal highway system, there is also an unequal distribution of MD and HD freight vehicles in lower-income communities and communities of color. Conversations about the decarbonization of the transportation sector must consider the deployment of zero-emission MD and HD freight vehicles in pollution-burdened communities.

Transportation agencies should engage in conversations about how to create an equitable MOD/MaaS system even with the barriers that prevent some commuters from utilizing the service. Agencies should have conversations with relevant stakeholders to reduce the number of dependencies MOD/MaaS have. Public Internet hubs, for example, may help individuals without a wireless data plan reserve rides using a mobile app or website. To eliminate the need to have multiple mobility provider payment accounts or a smartphone, decision-makers could consider the use of smartcards. "Compared to a universal payment app, smartcards do not require a smartphone and may represent a lower barrier for low-income riders" (ARCADIS 2017, 26).

Similar to MOD/MaaS adoption, other agencies need to be involved to ensure equitable CAV adoption. Expanding Internet connectivity, which CAVs rely on, will be an integral component of equitable CAV adoption, too. Cellular or satellite Internet providers will need to be involved in discussions to ensure rural communities, which may not currently have strong 4G networks, have the infrastructure necessary to be reachable by CAVs.

There is currently a lack of data on travel information and travel needs for underserved populations; therefore, their travel needs and preferences are not adequately modeled, resulting in biased projections. This could affect CAVs' ability to serve the population equitably.

Agencies should also implement policies to encourage neighborhood revitalization around vertiports while mitigating the potential local effects (e.g., gentrification). DOTs and MPOs can promote AAM use cases that benefit the whole community (e.g., emergency response and aeromedical transportation).

Potential Unintended Consequences. EV charging infrastructure must be equitably distributed. This is especially important in lower-income communities, whose residents typically have less access to secure garages or permanent parking spaces where a charger is accessible. These investments in charging infrastructure, however, should be predicated on extensive community engagement. Installing chargers in low-income neighborhoods and communities of color where there are few EVs, without having done extensive community engagement, can exacerbate mistrust and concerns about gentrification.

CAVs pose significant workforce concerns. Training and certification programs that consider how professional drivers will be put out of the workforce by automation will be critical to ensuring social stability (ARCADIS 2017, 21).

A side effect of CAVs may be an increase in travel demand and congestion with commuters more willing to commute long distances if they can do something other than drive the vehicle. It may also lead to more congestion because it may make vehicle travel accessible to groups who do not drive now or drive less than they might like, resulting in both positive and negative impacts. This could affect communities that have been made vulnerable more if they have less flexibility in work location, for example.

If meaningful, equity-forward decision-making processes are not established, a disproportionate share of the negative environmental consequences of AAM may be felt most by communities that have been made vulnerable. Examples of such negative externalities include the impacts of flight paths (i.e., noise) on low-income and minority neighborhoods and concerns about gentrification and displacement around vertiports. If maintaining and improving the current functioning systems (e.g., public transit), people who rely on them could become stranded as budgets for these services deteriorate (National Association of City Transportation Officials 2019, 20).

Hurdles and Potential Obstacles to Implementing Strategy. Even with physical infrastructure and subsidies in place for the purchase of EVs, there could be barriers to the equitable adoption of EVs. The lack of access to reliable and affordable charging is a significant barrier to adoption that agencies will need to grapple with and overcome (Hsu and Fingerman 2021). Contactless payment systems on the EV chargers or exclusive membership requirements could limit adoption among certain groups.

MOD/MaaS services pose payment access challenges that could exacerbate inequities or create new ones. MOD providers often require users to have access to a credit or debit card for registration or payment. Allowing cash payment can bridge the digital divide and provide heightened access to individuals without access to a credit card. Further, limited access to Internet service or wireless data in certain communities may prevent people from reserving rides using a mobile app or website. This disproportionately affects traditionally low-income, unhoused, and formerly unhoused communities, and those who have been made disadvantaged.

MOD/MaaS drivers may also play a role in creating an inequitable system. If drivers can view a trip's origin and destination and want to avoid a particular area of town, they may cancel a ride. This could lead to challenges in obtaining rides in those areas. Policies that limit drivers from screening rides in this way may play a role in creating a more equitable MOD/MaaS ecosystem.

Owner(s) of Policy or Strategy. The legacy of continuing transportation inequities, whether speaking of limited practical access or disproportionate burden loads, involves issues—both historic and current—that extend beyond the purview of a transportation agency. Even so, transportation opportunities and consequences can prove to be all-too-visible points of friction. While agencies may not be responsible for solving underlying socioeconomic problems that aggravate the transportation inequities that emerge, they would be well-advised to demonstrate the capacity to take explicit and effective recognition of them.

Range and Timeframe of Effectiveness. This will be a current issue for the foreseeable future.

Policy Brief 9: Practice Early Stakeholder and Community Engagement

The purpose of the following policy brief is to raise awareness of measures that could enhance the agency ability to manage and mitigate risk through stakeholder and community engagement. The brief is intended to create an organizational consciousness of how this type of engagement can widen the basis for agency risk management externally while also connecting risk management more directly with routine operational and planning activities.

The following brief details a program for monitoring risks actively and engaging in processes that could mitigate overall exposure to the risks detailed in the risk register.

Description. Community and stakeholder engagement can be important for ensuring that everyone has the opportunity to participate in the decisions about emerging transportation technologies that affect them. Public participation should serve a dual purpose and act as a bidirectional conversation—helping educate external stakeholders and the public about emerging transportation technologies while building institutional and community support and helping public agencies and service providers address community concerns. Public participation also provides an opportunity for public agencies to learn from the public and external stakeholders, gathering invaluable local, and institutional knowledge from those who live and work in the community. In Sherry R. Arnstein's *Ladder of Public Participation*, she writes about the ways citizens and agencies interact and the social hierarchies that exist between these groups. Community participation is defined as a categorical term for "citizen power" in that it allows individuals who are typically excluded from political and economic processes to be deliberately involved in planning for and making decisions about the future (Arnstein 1969). Further, the American Planning Association describes citizen participation as an inclusive process that helps ensure planning outcomes are equitable.

Proactive public engagement is imperative for all types of transportation projects. It is even more important for innovative mobility as new modes and concepts (and associated impacts) are not often widely understood outside of the transportation field. Proactive public engagement can foster meaningful involvement and ensure fair treatment, so no neighborhood or group bears a disproportionate share of positive or negative consequences from innovative mobility.

Efficacy: How Will This Help? Collaborating with and among MPOs and city and state DOTs to create a shared vision of transportation investments across a region is critical. Because individuals work and live in a region and are not bound by municipal or state jurisdictional lines, agencies should work together to create complementary transportation initiatives. Working collaboratively among a region's DOTs or across MPOs can also be challenging if priorities or perspectives are different. Finding common agency goals and tackling how emerging mobility technologies influence (positively or negatively) these goals can be an impactful place to start in encouraging agencies to develop unified approaches (U.S. DOT, FHA n.d.).

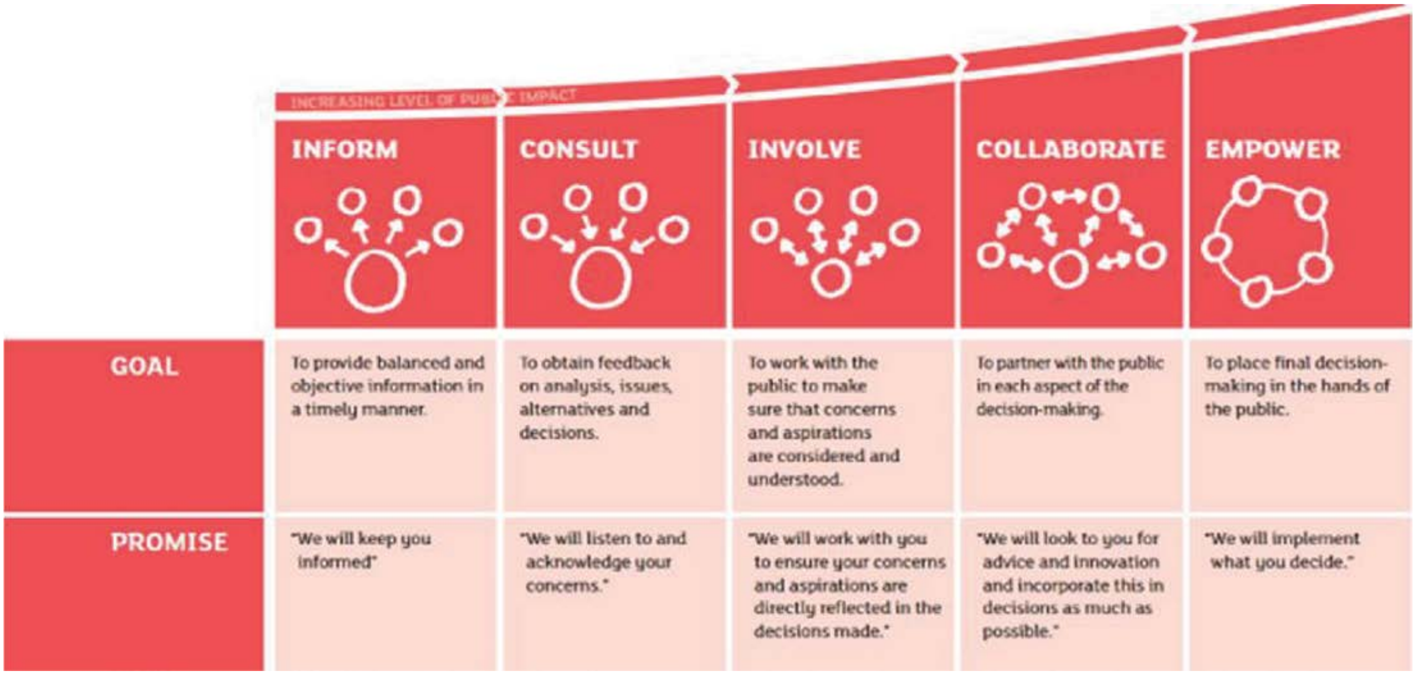
In addition to cross-agency communication and collaboration, there are many reasons for agencies to engage stakeholders and the public. For many years, state and federal laws such as the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA) have required public hearings to precede official decisions. While environmental processes such as CEQA and NEPA may be an effective tool for assessing the technical viability of innovative mobility deployments, early, deep stakeholder and community engagement is important to understand and address potential concerns. For example, this could include affording businesses and residents the ability to provide input on proposed changes to on-street rights-of-way, such as the addition of EV charging or an AV loading zone. It could also involve incorporating MOD and AAM into planning processes and documents.

How to Apply the Strategy in Practice. The International Association for Public Participation developed a framework that describes a spectrum of participation, ranging from least to greatest influence over decision-making in public processes (see Figure D.1).

The spectrum ranges from informing the public to increasing levels of public impact on outcomes, such as collaboration and empowerment. Within these engagement categories, there is a multitude of engagement strategies agencies can employ.

Common engagement methods include town halls, public hearings, open houses, focus groups, small group discussions, workshops, and peer exchanges, but forms of public engagement change as agencies work to engage the public in increasingly influential ways. Engagement practices will often vary based on an agency's policies, procedures, and local customs. For example, Washington, DC, has typically opted to receive feedback through neighborhood councils. Other jurisdictions have used public hearings, town hall meetings, and staff review processes. Some municipalities have provided municipal staff and regulatory agencies wider authority to develop and manage policies, such as public comment periods and administrative law hearings. Flexible and collaborative public processes often reflect best practices in policymaking, planning, and problem-solving because they can reduce conflict (and litigation) among stakeholders while advancing shared goals.

In addition to these traditional engagement methods, technology-enabled strategies can also be employed. For example, during the planning stages of New York City's Citi Bike, a bikeshare program, the municipal DOT conducted extensive multilingual public outreach which included hosting 159 public meetings, 230 stakeholder meetings, and use of an interactive planning map to identify potential bikeshare stations. This multichannel approach to stakeholder and community engagement yielded over 65,000 comments. This process also culminated in



Source: International Association for Public Participation (n.d.).

Figure D.1. International Association for Public Participation framework.

2,881 community-suggested bikeshare station locations for city consideration. Also in New York City, Rebuild by Design's efforts to build infrastructure that creates a more weather-resilient lower Manhattan in response to Hurricane Sandy has led to many innovative, creative engagement strategies. As one example, the research team utilized a storefront in the community as a home base for research team members, government officials, and the community to work alongside each other and make planning decisions together (Rebuild by Design Organization n.d.).

Stakeholder Considerations. The following are stakeholder considerations for this policy brief.

- **Stakeholder versus Community Engagement.** Community engagement is a process that involves the public in the transportation decision-making process. Community engagement provides the public with the information they need to be involved in a meaningful way and communicates to the public how their input influences the decision. In contrast, stakeholder engagement involves those who are affected by an action in the decision-making process. Although federal definitions of environmental justice often focus on equity around race, ethnicity, disability, and income, public agencies may consider expanding the definition of underserved populations to include other groups facing mobility challenges, such as older adults and zero-vehicle, single-parent, and non-English-speaking households. By broadening engagement considerations, public agencies can better leverage the potential benefits of emerging transportation technologies to enhance access and mobility among a broader segment of the community, particularly those with unmet transportation needs.
- **Adaptation in Community Engagement.** Emerging mobility technologies can severely disrupt the existing passenger and freight mobility ecosystems that exist today. The degree to which these new technologies transform the urban transportation environment, equity concerns, safety, and physical infrastructure will partially depend on what insights are gleaned from public engagement efforts. Without meaningful citizen engagement, planners and policymakers risk perpetuating social injustices, limiting community resiliency, and creating transportation

systems that do not benefit those residing in the neighborhood. Adaptive community engagement is important to ensure the method of engagement is suitable to the community's population. As a project evolves and as circumstances change, this may also lead to necessary adaptation in community outreach methods.

Equity of Distribution of Costs and Benefits. As the American Planning Association mentions, to ensure components of the future's transportation system do not perpetuate the inequities of today's transportation system, agencies must develop stakeholder and community engagement processes that encourage active participation and partnership from a cohort that represents the diversity of the community. Some community members, for example, may not be able to attend or feel comfortable attending a public hearing due to physical limitations, language barriers, or their work schedule. Bringing community engagement efforts to places in the community that feel accessible to residents can be a good place to start in ensuring an equitable distribution of costs and benefits from all emerging mobility technologies.

Potential Unintended Consequences. There are some risks with stakeholder and community engagement. Examples of potential challenges include the following:

- Project and process impacts (e.g., direct, indirect, and catalytic effects of a project or stakeholder engagement/community outreach activities).
- Disrespectful, malicious, inflammatory, obscene, intolerant, inappropriate, or illegal conversations.
- Public criticism of the process, proposal, or participants in the process.
- Using stakeholder and community engagement for political ends.
- Unrealistic expectations (this can be from the public or the agency leadership).
- Bias/predetermined outcome.
- Community confusion about a project, policy, or proposal if materials about the technology are not comprehensive.
- Overzealous participation (e.g., some participants speak louder than others making it difficult for everyone to have a voice).
- Meaningful engagement could slow the introduction of emerging mobility technologies.
- Lack of consensus building.
- Development of solutions that are difficult to scale.

Engaging the public and stakeholders openly, honestly, and without predetermined outcomes can help mitigate many of these challenges. Additionally, providing opportunities to engage in multiple ways, both physically and virtually, can help expand the accessibility of community and stakeholder engagement.

Hurdles and Potential Obstacles to Implementing Strategy. Each agency has a unique structure, processes, and legislative requirements governing engagement. Engagement type and how engagement is conducted will vary substantially based on the type of agency, type of proposal being considered, and legislative requirements (e.g., California has the Brown Act, which has specific requirements regarding public meetings that differ from similar legislation in other states). Such engagements may require changes in job descriptions and agency personnel. This is not an issue unique to managing risk from emerging and disruptive technologies and so should be an effort that takes a whole-of-agency approach to implementation and evaluation. Some other hurdles present themselves as follows:

- Engagement fatigue.
- Distrust of the public agency or government.
- Difficulty in public speaking or engaging in some types of settings.
- Lack of participation by stakeholders or the public in the process.

- Language barriers.
- Health and safety considerations (e.g., pandemic).
- Digital divide/computer literacy (e.g., unable to participate in engagement methods).
- Resource availability and cost (e.g., lack of resources to conduct effective stakeholder and community engagement).

Owner(s) of Policy or Strategy. This is an activity that could certainly involve agencies' public engagement teams but should also involve the private transportation providers who will be implementing the emerging technologies.

Range and Timeframe of Effectiveness. Community and stakeholder engagement should be conducted routinely throughout planning and implementation processes.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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