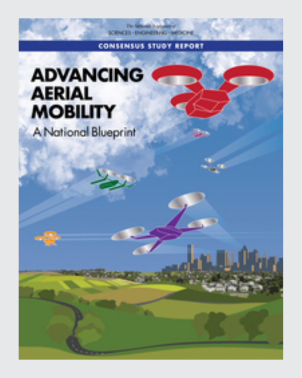

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ADVANCING AERIAL MOBILITY

A National Blueprint

Committee on Enhancing Air Mobility—A National Blueprint

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
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Preface

In 2018, the National Aeronautics and Space Administration (NASA) asked the National Academies of Sciences, Engineering, and Medicine to undertake a study to evaluate the potential benefits and challenges associated with advanced aerial mobility, an emerging technological development that can be simultaneously transformative and disruptive for the nation's aviation infrastructure and industry. Although the statement of task referred to "urban air mobility," while this study was under way the aviation community—and NASA itself—increasingly used the term "advanced aerial mobility," of which "urban air mobility" is considered a subset (albeit the most challenging one). The committee therefore chose to use advanced aerial mobility to capture the broader range of opportunities and operations that are being discussed.

The National Academies formed a committee that met three times between spring and fall 2019. This is a dynamic subject that was changing as the committee was finalizing its report and even during the report's review. Nevertheless, the committee sought to provide findings and recommendations that will help NASA and others in the aviation community foster an environment in which the nation can maintain its leadership in developing, deploying, and embracing new technology that opens up new opportunities. Whether through drone delivery of goods in urban environments, linking rural areas to population centers through passenger and cargo aviation, or an entirely new method of passenger travel within a metropolis and its surrounding areas, advanced aerial mobility can make aviation a part of daily life.

Such benefits do not come without challenges. This committee also sought to ensure that the foreseen problems that will inevitably arise from such cutting-edge technologies can be mitigated during development and that the unforeseen problems are discovered through processes established to safely test vehicles and methods of operation. By addressing these problems proactively in collaboration with other federal agencies, NASA can facilitate the integration of advanced aerial mobility into the national airspace infrastructure safely and with minimal negative impact on general aviation and the public-at-large.

It is the goal of this committee that this report reflects both the forward-thinking optimism and the caution that such a transformative technology merits.

Nick Lappos, *Chair*
Committee on Enhancing Air Mobility—A National Blueprint

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Eric Allison, Uber Elevate,
Chris Brown, Independent Consultant,
Stephen P. Cook, Northrop Grumman Corporation,
Michael R. Garvin, Jr., Ascent Global Logistics,
Michael J. Hirschberg, Vertical Flight Society,
James L. Kirtley, Jr., NAE,[1] Massachusetts Institute of Technology,
Andrew Lacher, The Boeing Company,
Karen Marais, Purdue University, and
Benjamin D. Marcus, AirMap.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Anita K. Jones, NAE, University of Virginia, and Brian Argrow, University of Colorado, Boulder. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Summary

Worldwide, there is a dramatic increase in the adoption of electric and hybrid aircraft for urban, suburban, and rural operations—what is commonly referred to as advanced aerial mobility. Advanced aerial mobility involves the emergence of transformative and disruptive new airborne technology supporting an ecosystem designed to transport people and things to locations not traditionally served by current modes of air transportation, including both rural and the more challenging and complex urban environments.[1] Incremental developments in many different fields such as computer software, electronics and sensors, energy storage, and electric aircraft are in the works. These technologies are transformative and promise to change the way that cargo and people are moved, affecting industries across the economy. The aircraft that are being developed are short-range, runway independent, and highly automated.

The use of electric motors and simplified electric controls to replace the complex transmissions and elaborate flight-critical components can dramatically reduce the number of flight-critical components, improving mechanical reliability. This promises to substantially reduce the manufacturing and operating costs of flight vehicles. This innovation in air vehicle design could enable a number of missions in urban and other environments that are now conducted by ground vehicles. Electric propulsion and increasingly automated flight may also improve safety, simplify maintenance and operation, lower noise, and improve ease of use.

Hundreds of different air vehicles are being developed with more than a dozen vehicle projects receiving major investment from private industry; these air vehicles are being developed by traditional aerospace companies as well as by many new entrants with little or no prior aviation experience. Many of these vehicle concepts are in very early stages of development. These entrepreneurs are creating a class of vehicles that have the attributes to succeed in changing transportation operations and can lead to fundamentally new capabilities. This new industry of vertical lift operations, the supporting ground infrastructure, and the required air traffic management systems will seriously challenge today's airspace monitoring systems and regulatory environment. The National Aeronautics

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[1] Although the statement of task referred to "urban air mobility," while this study was under way the aviation community—and the National Aeronautics and Space Administration itself—increasingly used the term "advanced aerial mobility," of which "urban air mobility" is considered a subset (albeit the most challenging one). The committee therefore chose to use advanced aerial mobility to capture the broader range of opportunities and operations that are being discussed. The committee would not change the report in any way if it were to change the focus to urban air mobility only. The findings and recommendations hold true for both advanced aerial mobility and urban air mobility. But the committee did feel it important to recognize that there are opportunities to start with non-urban areas and activities and to indicate that the benefits of these new technologies are not only to urban areas. This report does not address concepts like unpiloted air transports, supersonic, hypersonic, and electrified aviation. In addition, small drones operating in Class A airspace generally do fall into the definition of aerial mobility.

and Space Administration (NASA) is uniquely qualified to provide the technical guidance for the U.S. government and its regulatory agencies like the Federal Aviation Administration (FAA), among others, to facilitate the adoption of these technologies and to create the regulatory framework to foster the growth of this vertical flight industry for the benefit of the aviation industry.

In early 2019, NASA asked the National Academies of Sciences, Engineering, and Medicine to conduct a study and develop a vision of the future of "urban air mobility" (UAM). (See the statement of task for the Committee on Enhancing Air Mobility in Appendix A.) The committee determined that UAM is but one subset in a much broader field of advanced aerial mobility, and NASA's own publications and management have adopted this broader term. Advanced aerial mobility can include providing services to rural and exurban areas as well as the more challenging urban areas.

NEW MISSIONS CAN FULFILL LATENT NEEDS

Advanced aerial mobility can bring about transformation in a number of industries (e.g., transportation, emergency response, and cargo/package logistics). However, it is important to ensure that societal benefits and costs of implementation are well understood using scenario-based analyses to assist, as all the applications will most likely not be evident until deployment is under way and users adapt to new capabilities. Being able to communicate benefits will aid in public acceptance and community outreach. NASA can play a key role, working with other involved government agencies as well as academia.

New capabilities can trigger missions beyond air taxi and package express, so that they might very well include security patrols for safety, rapid response for emergencies and fires, police patrol, and even the delivery of life-saving medicines during emergencies. It is possible that, like the cell phone and the computer, new and as yet unseen missions filling what will become important economic issues, can be enabled as this new aerial technology develops.

The committee believes that the commercial cargo market appears to be one of the visible "initial adopters" of autonomous air vehicle technology/capability for rural domestic cargo operations. This would include "last mile" local package delivery and "middle mile" cargo as one of the first applications fielded by companies, including those that will ultimately deliver something to an end-customer.

Recommendation: NASA should, within the next year, establish strategic partnerships with first adopter cargo logistics providers and relevant manufacturers. The partners should focus on maturation of technologies aimed at deploying autonomous cargo drone delivery of small, medium, and large size within 3 years. (Chapter 3)

VISION OF THE FUTURE AIRSPACE AND AIR TRAFFIC MANAGEMENT ENVIRONMENT

The committee's vision of the future airspace system does not necessarily constrict any class vehicle to one restricted block of airspace; in fact, the committee and the majority of those interviewed embrace the concept of using technology to network all vehicle types to control traffic, separation, and paths. For this reason, it does not envision different infrastructures but rather one infrastructure that has levels of complexity based on the user of that infrastructure. The committee believes that, properly harnessed, a data sharing network of flight vehicles can achieve breakthrough airspace allocations. This future data sharing network can be seen as a utility provided for the advanced aerial mobility operators to facilitate their best utilization, promote safety, and provide practical traffic management and separation without burdening each vehicle with multiple sensors and their reliability, weight, and cost.

As an illustration of this digital network concept, through digital means, FedEx handles over 20 million pieces each day in the week prior to Christmas and controls and tracks each piece within a few meters throughout their journey. Similarly, Google uses networked cell phone tracking to create a real-time traffic reporting system across the United States that accurately displays trip times on all major roads.

It is important to consider a phased, iterative approach to development, testing, and introduction of new capabilities. It is not reasonable for a system of this degree of multidisciplinary complexity, with as many stakeholders involved (including the general public) and with regulatory involvement at every step, to self-assemble out of a mass of uncoordinated innovation efforts. Rather, coordination leading to interoperability and standards is essential.

Recommendation: NASA, in coordination with the FAA, should perform research to extend unmanned aircraft system traffic management concepts to accommodate emerging advanced aerial mobility traffic in all classes of airspace. (Chapter 3)

UNITED STATES UNIQUELY POISED TO LEAD

The FAA has a sole mandate to promote safety in the National Airspace System and the authority as regulator over the airspace system. Other federal agencies have an interest in the National Airspace System, whether for national security, environment, or other factors. NASA has research capability but no authority to regulate or decide on technology implementation for the National Airspace System. This arrangement has proven effective at driving exceptional safety, but it constrains aviation to a modest evolutionary pace. Maturing technologies are creating transformational new capabilities in flight that promise to expand the use cases for aviation across the economy and increase the scale of activity in the National Airspace System by orders of magnitude. While U.S. leadership in aerospace is in the national interest, no entity within the U.S. government has the clear mandate to promote commercial aviation or the development, adoption, and commercialization of new technologies or applications thereof.

Implementing a versatile advanced aerial mobility system with multiple applications and users is a complex, multidisciplinary challenge. No entity, public or private, possesses all the necessary skills. Nor does any single entity currently have sufficient oversight/responsibility to effectively make advanced aerial mobility a reality, while maximizing societal benefits, within the next 3-5 years.

Historically, the United States has led the world in aviation technology. Through a mix of strong academic investment in human and research capital, the development of critical artificial intelligence and autonomous technologies, and the availability of investment capital and the technical savvy of investors, the United States is potentially poised to continue this trend. Also of importance is the U.S. urban/suburban/rural social and physical infrastructure, which appears ready to support new modes of aerial transportation.

Another advantage the United States has, in the development of these new technologies, is a strong and knowledgeable government regulatory establishment, with FAA, Department of Defense (DoD), and NASA technologists who are prepared to lead with guidelines. What is needed to assure continued U.S. leadership is a clear statement of national will and a clear master plan and national commitment to execute it.

Recommendation: In order to formulate a U.S. Joint Advanced Aerial Mobility Master Plan, NASA and FAA should form a partnership to manage responsibility and accountability across the various stakeholders to participate in the development of the Master Plan.

FROM URBAN AIR MOBILITY TO ADVANCED AERIAL MOBILITY

NASA is widely viewed as an objective, respected repository of knowledge and research capability, a trusted leader in new concepts for airspace management and aeronautics, and an honest broker in promoting U.S. leadership in aerospace. Admittedly, NASA has limited authority to translate ideas into implementation. The FAA has the most authority to implement, and other federal agencies such as the Federal Communications Commission, National Institute of Standards and Technology, Department of Homeland Security, DoD, Department of the Interior, and U.S. Department of Agriculture are key stakeholders. But NASA and the FAA have a long partnership, and NASA can serve as a risk-taking, innovative partner to the FAA in the development of advanced aerial mobility.

Popular media attention to advanced aerial mobility topics usually focuses on home package delivery by small electric aircraft, and urban air taxi services. However, urban air taxi service for the general public, due to its requirements for vehicle performance, safety, sophisticated operations, infrastructure, operating costs, and system scale and tempo, is one of the most demanding applications of advanced aerial mobility. It is an attractive application once the system capabilities are in place. However, it is not possible to implement UAM or achieve its vision without first building and gaining experience in other less demanding areas of advanced aerial mobility. This is already happening: during the course of this study, several new commercial test operations involving package delivery in rural areas began, or were announced, and several new piloted passengers-carrying vehicles were unveiled.

The committee believes that the current development plan for this infrastructure change involves a graduated set of applications, starting today with less challenging and more controlled lower-density locations as test cases for the development of vehicles, control schemes, and networking concepts. The plan is to solve basic issues first, then gradually increase complexity by bringing the fielded solutions into more suburban and then urban environments, where increased population, obstruction density, and traffic density create more challenges. The committee believes that to restrict the discussion only to urban operations defeats this natural development progression and creates the impression that only urban environments warrant examination and will benefit. Additionally, the concepts that were presented to the committee by the developers of actual flight systems did not differentiate these vehicles by their operating environment; the developers are bringing the same class of vehicles into the urban, rural, and mixed market arenas.

The committee concluded that numerous other applications that are less demanding can serve as opportunities to build experience and refine technology on the way to establishing the full set of capabilities required for urban air taxi services. These applications can also play an important role in establishing societal acceptance of the technology. Near-term applications can include cargo delivery, inspection, and surveillance operations in less densely populated areas. Applications can include emergency medical services, first responders, disaster relief, corporate transport, cargo logistics, and others. Given the new capabilities that technology delivers to flight, the applications of advanced aerial mobility are wide-reaching and difficult to foresee.

CHALLENGES TO ACHIEVING THE VISION

Achieving this positive vision for advanced aerial mobility will not be easy. Acceptance of advanced aerial mobility technology will be especially challenging unless significant coordination, education, and agreement is obtained with public and private entities. It will take major changes to current aviation systems, particularly in how the National Airspace System safely integrates new technologies to manage and integrate operations at high traffic densities. In some ways, the nation is not ready for this transformation, and there are serious barriers to entry by new participants, such as small start-ups. There are mismatches between the exuberance of entrepreneurs and early investors and the realities of implementation, such as traversing an aircraft certification system that has developed over generations to address more traditional forms of air transport. There are also potential negative impacts such as community noise concerns, introduction of new safety risks, an increased carbon footprint, and other related societal concerns.[2]

Success of advanced aerial mobility systems will be dependent on several factors if they are to be accepted from an economic, social, and regulatory standpoint. Some of these factors are as follows:

- *Safety.* Advanced aerial mobility will have to demonstrate the high safety levels expected by the public for modern air transportation systems.
- *Security.* Emerging technologies present new cybersecurity risks and vulnerabilities that will have to be managed.
- *Social acceptance.* New products or services applying advanced aerial mobility must gain the trust and support of the public, taking into account multiple factors.
- *Resilience.* Contingency management, the ability to manage the expected and the capability to recover from the unexpected, will be a key to success.
- *Environmental impacts.* Factors such as noise and visual impact from air vehicles on the environment and nonparticipants, as well as greenhouse gas emissions and any associated air pollutant emissions, will have to be minimized to acceptable levels.

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[2] See M. Basner, C. Clark, A. Hansell, J.I. Hileman, S. Janssen, K. Shepherd, and V. Sparrow, 2017, Aviation noise impacts: State of the science, *Noise Health* 19(87):41-50. See also R. Cointin, N. Sizov, and J.I. Hileman, 2016, "U.S. Civil Aircraft Noise Annoyance Survey Design," presented at Inter Noise, Hamburg, https://pdfs.semanticscholar.org/016c/ac9e87b25ffb810dc54046ff456f1fded110.pdf. See, generally, the Pennsylvania State University's "NoiseQuest" website at https://www.noisequest.psu.edu.

- *Regulation*. New rules to accommodate the technology as well as to define its integration into the National Airspace System will have to be created.
- *Scalability*. Any successful approach to advanced aerial mobility will need the capability to scale as the market segments emerge and grow.
- *Flexibility*. With any disruptive new initiative, flexibility is critical as new use cases and operational concepts emerge.

HIGH-LEVEL ARCHITECTURE AND REQUIREMENTS ARE NEEDED

A National Airspace System that delivers safety, increasingly autonomous system access, and scalability yet that makes few constraining assumptions about specific anticipated flight operations will deliver flexibility to explore applications of advanced aerial mobility and to adapt gracefully to future increases in scale and capability. Although the National Airspace System is the FAA's responsibility, the committee concluded that NASA can play an important role in achieving the increase in scale and capability of the National Airspace System.

A definition of a series of successively more complex capability milestones and the architectural components of the system that will support them is needed. These requirements sets embody progressively more sophisticated operations in the National Airspace System that deliver increased capabilities and scale to the system. These requirements sets serve as a target for standards development and the systems based on them, and ultimately new flight rules sets for the National Airspace System. Architectural decisions include specifications sufficient for future standards and implementation development in areas such as the following:

- System architecture framework—defining the principal elements, functions, and interfaces of the system;
- Communications—assumed communications capabilities, including decisions for spectrum, data exchange, and cybersecurity standards;
- Approaches to adapting architectural function and components over time; and
- Evolution of existing safety evaluation approaches.

Recommendation: NASA should prioritize research that develops architectures, requirements, and supporting technologies to enable integrating advanced aerial mobility into a future National Airspace System. (Chapter 3)

THE IMPORTANCE OF PUBLIC ACCEPTANCE

While certification of vehicles and integration into the airspace system will be challenging, there are additional barriers to consider. Public acceptance of advanced aerial mobility, particularly noise aspects and its psychological factors, is perhaps one of the biggest challenges along with safety. Failure to address these issues could hinder advanced aerial mobility implementation. Noise from aircraft and other transportation modes is a complex topic spanning acoustics, the physiological way humans experience noise, and the psychological perceptions listeners have of the source of the noise and what it represents to them. A large body of research spanning this area has been conducted over the past century, with learning outcomes relevant to modern aviation. Early operations may start with a less intense acoustical impact on bystanders (e.g., less frequent operations in rural areas) and with strong positive social impact (e.g., emergency medical services, search and rescue, and disaster relief). These applications can be a valuable test bed to learn and refine low-noise operations as well as to actively shape positive public perception of the technology.

Recommendation: Research should be performed to quantify and mitigate public annoyance due to noise, including psychoacoustic and health aspects, from different types of advanced aerial mobility operations. NASA should facilitate a collaboration between relevant government agencies—including FAA, Department of Defense, National Institutes of Health, academia, state and local governments, industry, original equipment manufacturers, operators, and nonprofit organizations—to prioritize and conduct the research, with responsibility allocated per a coordinated plan and accountability for delivery incorporated. The research should be completed in 2 years. (Chapter 2)

Recommendation: NASA should facilitate a collaboration with other relevant government agencies—the FAA, Department of Commerce, and Environmental Protection Agency—and industry—original equipment manufacturers and operators as well as academia and nonprofit organizations—to conduct scenario-based studies to assess societal impacts (e.g., privacy, intrusion, public health and welfare, transparency, environmental, inequity) of advanced aerial mobility vehicles and associated infrastructure. These studies should recommend a path to implementation that prioritizes maximum public benefits. (Chapter 2)

THE NASA NATIONAL CAMPAIGN

The NASA National Campaign (formerly Grand Challenge) program seeks to improve advanced aerial mobility safety and accelerate scalability through integrated demonstrations of candidate operational concepts and scenarios. This goal is supported by five overarching objectives: Accelerate Certification and Approval; Develop Flight Procedure Guidelines; Evaluate the Communication, Navigation, and Surveillance Trade-Space; Demonstrate an Airspace Operations Management Architecture; and Characterize Vehicle Noise. NASA's continual refinement of the National Campaign program based on feedback of industry as central players is commendable (and essential) given the many opportunities (but unknowns) related to new entrants and entrepreneurial approaches.

One of NASA's priorities for the National Campaign is to pioneer the research, systems, and concepts of operations to enable advanced aerial mobility in the National Airspace System. This is a critical enabler with benefits for all, as it will assist in driving clarity from regulators with respect to system architecture, operations, and regulatory requirements. However, the structure and schedule of the National Campaign to drive these goals means that many companies are either unable or unwilling to participate. An additional outgrowth of NASA's work in the National Campaign program is the generation of data, best practices, and resources focused on advanced aerial mobility, and other findings that are valuable to all U.S. participants in the industry. If captured and disseminated effectively, these assets can accelerate progress across the industry and promote continued U.S. leadership in aerospace.

Recommendation: In partnership with industry, NASA should continue building on and enhancing the National Campaign program and develop its learning outcomes into formalized best practices, tools, resources, and training programs available to all U.S. stakeholders. (Chapter 3)

TESTING, SIMULATION, AND CYBERSECURITY

Testing and simulation capabilities today are not adequate to ensure safety in complex, software-intensive autonomous systems. Traditional testing and simulation alone are not adequate to ensure safety in complex, software-intensive systems like advanced aerial mobility. Traditional hazard analysis and safety engineering modeling and analysis tools are not adequate to assess and certify such complex systems. NASA, in coordination with the FAA, can provide education on the need for new approaches beyond testing and simulation to the advanced aerial mobility development community.

Recommendation: In coordination with the FAA, NASA should support research on new, more powerful safety analysis tools that are widely used today that can be applied to software-intensive advanced systems. (Chapter 4)

Current cybersecurity approaches that rely on threat analysis, maintaining impenetrable boundaries, and focusing primarily on information security will not be adequate for advanced aerial mobility missions involving safety-critical operations performed by automated systems. Current airworthiness hardware and software cybersecurity techniques do not accommodate advanced aerial mobility platforms. NASA has initiated research into the area of complex autonomous systems to include leveraging of cybersecurity-related investigations performed by other agencies. The committee believes that this is important research.

Recommendation: NASA should conduct research and development on cybersecurity for advanced aerial mobility systems. (Chapter 4)

NASA does not establish standards, which are the purview of the FAA. Nevertheless, NASA demonstrates techniques, which are then incorporated into certification policy or standards, and those in turn are adopted by FAA.

Recommendation: Working with the FAA certification experts, NASA should develop potential software and hardware certification techniques and guidelines to verify and validate the performance of complex software and hardware, including nondeterministic functionality. This NASA research into methods to demonstrate performance will provide valuable input to the FAA, including material for advisory circulars, to help applicants in the certification process. (Chapter 4)

CONTINGENCY MANAGEMENT

Due to the expected increase in the number of aircraft operations per day, and an observed steady-to-decreasing pilot training pipeline, autonomy for contingency management will be an essential component of advanced aerial mobility. Contingency management is the capability to manage, reduce, or eliminate unanticipated risk to persons, property, or other aircraft due to off-nominal events associated with vehicle operations. Encoding well-established contingency management procedures into autonomy will provide a rich baseline capability for automated contingency management in the near term. These procedures can be certified using a combination of existing and emerging certification practices to provide assurance that they will activate and execute safely and correctly. Software-based evaluation tools can be applied to rigorously evaluate autonomy for well-defined deterministic contingency management to reduce the manpower and cost required to use today's certification practices.

Real-time data processing will be required to enable appropriate autonomous perception, decision-making, and action outcomes in contingency management cases not recognized and matched with established procedures. In such cases, pilots, especially inexperienced pilots, would also be required to ingest real-time data and adapt their situational understanding and decisions in real time. No guarantees of correct response are possible when either autonomy or pilots must learn in real time, yet learning and acting offers a better chance of survival or recovery than shutting down.

Advanced aerial mobility will typically rely on a variety of real-time data sources for detect and avoid, traffic coordination, and access to data updates—for example, weather and winds. Cyber resilience, the ability for a vehicle or local vehicle group to safely continue a flight operation despite loss or corruption of one or more datalinks or server connections, is an essential component of advanced aerial mobility contingency management.

Recommendation: NASA should conduct research, development, and testing of autonomy for contingency management to support safe advanced aerial mobility. (Chapter 4)

FLIGHT TESTING RESOURCES

A key aspect of advanced aerial mobility is that it enables new applications for which aircraft were previously not feasible. The operational details of what works best for these new applications is not well understood. There is a lack of suitable flight-testing capability today. Unmanned aircraft must be tested under special conditions, which in most cases requires flight testing at purpose-built test ranges or, in some cases, in restricted airspace. This demand for testing implies a need for locations where companies can do extended testing and development with ongoing consistent access to airspace, the ability to access and modify infrastructure on the ground to support flight test scenarios and application development, and overall ease of access to the test range and ease of working at the range.

Recommendation: NASA, in coordination with the FAA, should make allocations of facility resources and airspace and regulatory accommodations to establish a continuous flight test capability that supports rapid development of the following:

- **Air vehicles;**
- **Flight operations practices;**
- **Surveillance and communications technologies/networks;**

- **Air traffic management systems, leveraging Unmanned Aircraft System Traffic Management construct and lessons;**
- **System-wide management systems;**
- **Noise reduction technologies and operations; and**
- **Ground infrastructure specific to various applications.**

This flight test capability should be designed to enable industry to innovate and commercialize its platforms/applications more rapidly. This effort can build on the progress and assets already in place from existing test range programs. (Chapter 5)

HELIPORTS AND VERTIPORTS

Construction of new heliports, vertiports, or other ground infrastructure will be costly and complex due to a lack of clarity in regulatory requirements for public facilities. There are tens of thousands of underutilized airports and large tracts of abandoned real estate throughout the country that could be converted for use by service providers. Although many new air mobility vehicles do not require runways, they can benefit from zoning, infrastructure, and airspace regulations that already exist at these airports and heliports. The FAA is soliciting industry through a formal request for information to create standards for vertiport design. Infrastructure enabling a UAM system will include vertiports, vehicle hangar and maintenance areas, and associated recharging/refueling infrastructure. A vertiport is a facility for allowing takeoff and landing of vertical aircraft. Because many of the aircraft that are currently envisioned may not have people onboard, are smaller than most helicopters, and may only carry small amounts of cargo, they may not be as large and structurally robust as heliports, although they may place other demands on infrastructure such as the requirement for electric recharging. A robust UAM system would have a multitude of vertiports serving a metropolitan area; hence, UAM infrastructure will necessarily be distributed rather than centralized.

Public-private partnership arrangements could be used to enable growth of distributed UAM infrastructure in a metropolitan area, while enabling this infrastructure to be a common carrier for different types of vehicles from different firms. This would enable competition and innovation in the UAM system.

Recommendation: A public-private partnership should be established to facilitate advanced aerial mobility implementation in a virtual environment to deliver as a near-term capability to define mobility systems and infrastructure requirements. This virtual environment should complement physical flight and operations testing. The partnership should be coordinated by NASA, in collaboration with the FAA and with coordinated allocation of responsibility among the FAA and other relevant agencies, industry (i.e., original equipment manufacturers and operators), and standards development setting organizations. For example, the group could focus on developing guidelines and solicitations for advanced aerial mobility infrastructure deployment. (Chapter 5)

The pace of demand growth will outrun the ability of any monolithic airspace system design to adapt and grow to meet the need, particularly if overseen solely by the public sector. It is thus of prime importance to enable and mobilize the private sector to innovate on higher performance airspace management technologies. As technology history has shown, this can be done, in part, with the public sector leading the research on the system topology and the protocols, data formats, and data exchange standards that define the broader system and giving private sector participants certainty as to what objectives to innovate toward.

Data exchange for advanced aerial mobility is diverse in content, size, and real-time update requirements. Detect and avoid and separation assurance applications require a common geospatial framework for aircraft state updates as well as communicating intent and air traffic control directives.

No public entity exists today with authority to establish and manage data standards for aviation data exchange. Standing up such a group would facilitate both the creation and evolution of data content and formats as advanced aerial mobility technologies and operations evolve.

Recommendation: A working group comprised of NASA, industry, academia, and the standards development organizations should prioritize research on the protocols, data formats, and data exchange standards that support advanced aerial mobility vehicles in a geospatial real-time system supporting safety-critical operations across the National Airspace System. The intent should be that the tools developed will provide the necessary clarity to catalyze and enable commercialization of system components by industry. (Chapter 5)

ORGANIZATION OF THIS REPORT

This report is organized into five chapters. Chapter 1 is an introduction to the subject of advanced aerial mobility. It presents a broad overview of the concept of advanced aerial mobility and how this development fits into the continuing history of aviation in the United States. Chapter 2 describes a vision for advanced aerial mobility, including the essential characteristics that advanced aerial mobility must embody, and along with Chapter 1 develops and discusses an overall vision for advanced aerial mobility. Chapter 3 discusses how to create an environment where initial operators can develop the market in collaboration with federal agencies. Chapter 4 details the critical developments necessary for a safe and secure advanced aerial mobility network and how advanced aerial mobility will need significant research into safety analysis tools for automated aircraft, for cybersecurity, and for contingency management. Chapters 2, 3, and 4 identify the barriers to achieving this vision and consider the impact of entrepreneurial approaches to advanced aerial mobility systems and how NASA can facilitate those efforts. Last, Chapter 5 projects a path forward for implementing advanced aerial mobility. It discusses how to achieve the vision of advanced aerial mobility for the country by overcoming institutional barriers, establishing public-private partnerships, and accommodating advanced aerial mobility vehicle development and deployment in the national airspace.

1

Introduction

Technological advances in electric propulsion and control systems, computer systems, sensors, precision position and navigation information, and other areas are facilitating the development and operation of new air vehicles potentially capable of safe, reliable, and low-noise flight, including vertical flight, with simplified vehicle operations or autonomy and with lower operating and maintenance costs than conventional aerial mobility. This transformation, which this committee refers to as advanced aerial mobility, is leading to an expansion of the potential opportunities where flight is utilized to accomplish tasks in industries across the economy and in ways that have the potential to be safe, environmentally responsible, and acceptable to the community. While in its infancy today, advanced aerial mobility has the potential to bring profound changes across passenger transport, cargo logistics, deliveries, and business and consumer services, in addition to broad second-order effects across these industries.

Advanced aerial mobility includes manned and unmanned, autonomous and pilot-supervised aircraft of any size and mission operating safely and responsibly in an integrated National Airspace System. These can include both electric and hybrid aircraft. The term applies less to specific aircraft than to the overall method of operations and purpose. By responsibly, the committee believes that participants of the integrated National Airspace System must meet high standards in terms of the overall integrity of the vehicle, its navigation system, and its adherence to assigned path and airspace. The diverse set of envisioned advanced aerial mobility operations range from commercial transport and air taxi services to drone surveillance and inspection in urban to rural regions (see Figure 1.1).

The committee's statement of task is to lay out a national vision for advanced aerial mobility and research recommendations that overcome the technical, regulatory, and policy barriers that sit between today and achieving the vision. Even in these early days, the dynamism in this space across vehicle development, new mission profiles, emerging applications, infrastructure requirements, and airspace system management makes this a challengingly broad topic to cover comprehensively. Yet, the criticality of charting out a national vision for advanced aerial mobility at this time cannot be understated.

The path to the routine acceptance of a new, disruptive transportation ecosystem is daunting. Challenges abound, as the global airspace in its present form was not designed to accommodate the levels of autonomy needed to make advanced aerial mobility scalable and thus a viable option. Success of advanced aerial mobility systems

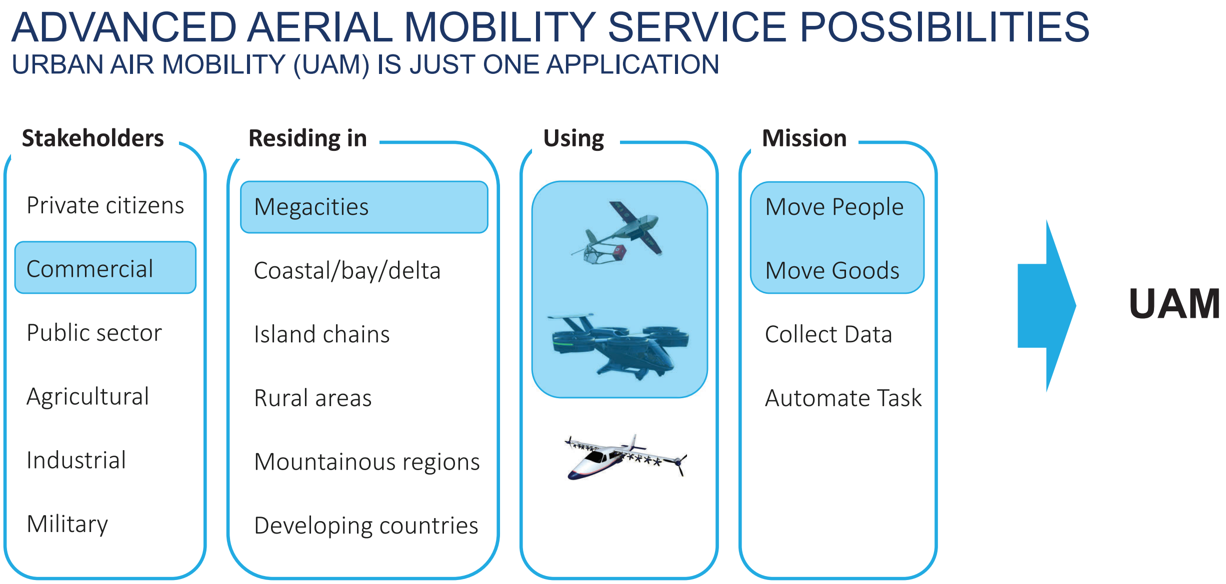
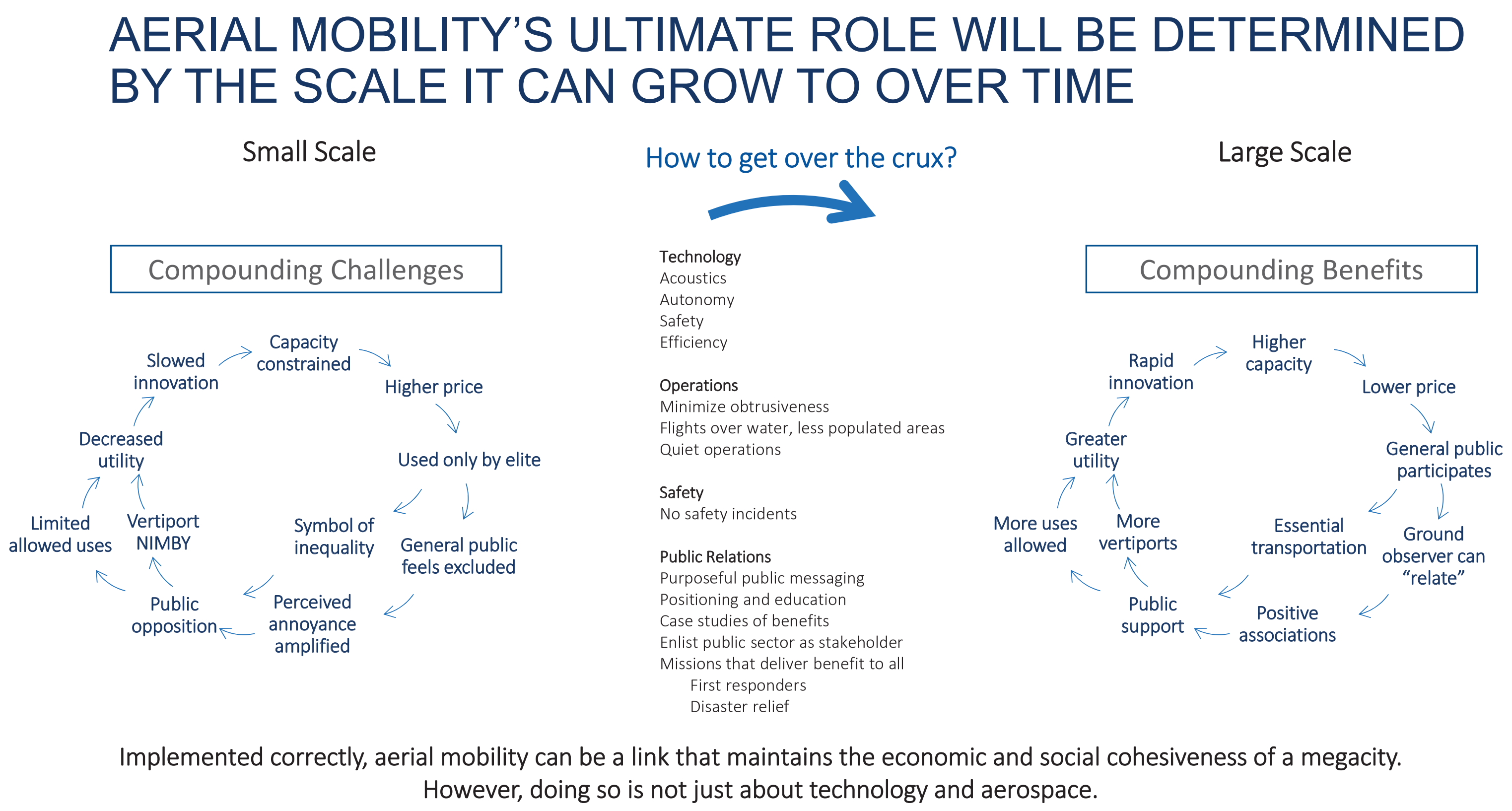


FIGURE 1.1 Advanced aerial mobility covers a diverse set of stakeholders, deployment environments, and use cases, not limited to urban air mobility.

will be dependent on several factors if they are to be accepted from an economic, social, and regulatory standpoint. Some of these factors are as follows:

- *Safety*. Advanced aerial mobility will have to demonstrate the high safety levels expected by the public for modern air transportation systems.
- *Security*. Emerging technologies present new cybersecurity risks and vulnerabilities that will have to be managed.
- *Social acceptance*. New products or services applying advanced aerial mobility must gain the trust and support of the public, taking into account multiple factors.
- *Resilience*. Contingency management, the ability to manage the expected and the capability to recover from the unexpected, will be a key to success.
- *Environmental impacts*. Factors such as noise and visual impact from air vehicles on the environment and nonparticipants will have to be minimized to acceptable levels.
- *Regulation*. New rules to accommodate the technology as well as to define its integration into the National Airspace System will have to be created.
- *Scalability*. Any successful approach to advanced aerial mobility will need the capability to scale as market segments emerge and grow.
- *Flexibility*. With any disruptive new initiative, flexibility is critical as new use cases and operational concepts emerge.

A key application area for new capabilities in flight is urban air mobility (UAM), air passenger and cargo transportation within or to/from a metropolitan area with vehicles ranging from small drones to passenger aircraft, including in some cases electrically powered vertical takeoff and landing capabilities. Although "urban air mobility" is the current, commonly accepted term, the committee considers UAM to be a subset of the overall subject, albeit the most challenging one. UAM presents an illustrative case study with respect to the factors enumerated above. For UAM to thrive, it must achieve large scale and therefore must gain public support and acceptance by society through demonstrating all of the other factors. In fact, if it fails to achieve large scale, it risks growing barriers from a societal acceptance standpoint (see Figure 1.2).



AERIAL MOBILITY'S ULTIMATE ROLE WILL BE DETERMINED BY THE SCALE IT CAN GROW TO OVER TIME

Technology
Acoustics
Autonomy
Safety
Efficiency

Operations
Minimize obtrusiveness
Flights over water, less populated areas
Quiet operations

Safety
No safety incidents

Public Relations
Purposeful public messaging
Positioning and education
Case studies of benefits
Enlist public sector as stakeholder
Missions that deliver benefit to all
    First responders
    Disaster relief

Implemented correctly, aerial mobility can be a link that maintains the economic and social cohesiveness of a megacity. However, doing so is not just about technology and aerospace.

FIGURE 1.2 On the left is a system dynamics model showing the challenges of a small-scale advanced aerial mobility system. General hostility to a system that appears to benefit only the elite or wealthy can inhibit growth of advanced aerial mobility. The benefits and dynamics of a large-scale system are shown on the right. The list in the middle shows the roadblocks that must be overcome to get to a large-scale system that is politically feasible and acceptable.

Four general areas need to be addressed:

- *Technology*. Technological advances will be needed to scale what exists today. These advances include acoustics and noise reduction, autonomy and software capabilities, ways to design safety into the system and to convince the users that risk is acceptable, and efficiency to overcome cost barriers.
- *Operations*. The public will not accept greatly increased flight operations over their homes and in their "airspace" unless noise and obtrusiveness, and the resultant effects on family and community life, can be minimized. Safe interoperability with all other aircraft in both controlled and uncontrolled airspace classes must be assured.
- *Safety and privacy*. The success of traditional transport systems has hinged on the ability of the industry to convince the public about its safety. Whether or not the fears are rational, success of advanced aerial mobility will require a very high safety record. The potential impact of advanced aerial mobility on privacy and security will need to be at publicly acceptable levels.
- *Public relations*. A public relations campaign will be necessary to overcome any natural fears or misunderstandings and to build trust in these new systems. This campaign will have to include purposeful public messaging, education, and case studies and demonstrations of benefits. Enlisting the public as stakeholders and advisors can also be effective. Part of the messaging and case studies will likely be services provided by other parts of advanced aerial mobility that will have the greatest impact and attraction by the public, such as first responders, disaster relief, crime reduction, and firefighting.[1]

Many of the early advances in aerial mobility are currently and will in the near future be made in nonurban areas, which are not as congested and have lower population densities. As the committee notes later in this report, introducing new forms of air transportation inside or outside of urban areas could have considerable community impacts involving safety, privacy, and environmental factors. Ultimately, the widespread adoption and success of advanced aerial mobility depends on understanding and mitigating these impacts, so that the desired public outcomes are designed into the system.

At this time, several government agencies have some responsibilities for overcoming challenges of large-scale advanced aerial mobility operation, but there are important gaps that need to be filled where the responsibilities should be assigned and coordination will be important in some areas. As can be seen in Figure 1.3, there are currently three areas of gaps or unmet needs for the private sector:

1. A mandate must be created within the public sector to deliver progress toward enhanced capabilities for the National Airspace System that enabled advanced aerial mobility, increasing automation and the emerging applications of flight it enables. This is not currently the responsibility of the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), or industry. Progress will require mobilizing the private sector, expanding and growing aviation applications, and overall leadership to promote advanced aerial mobility in the United States.
2. Various capabilities within the public sector are required to successfully achieve the goals of an advanced aerial mobility vision, but these exist currently only at varying levels. Required capabilities include system engineering, industry-government interfaces, necessary standards, program management, public-private partnerships, systems delivery, and certification.
3. Authority needs to be in place for making decisions about advanced aerial mobility system-wide architectures, concept and systems definition, and rulemaking.

There is a need for an assigned overarching entity that is chartered with coordinating the necessary stakeholders and establishing an advanced aerial mobility system along some pre-stated goals. Without such coordination at the federal government level, the progress will be hindered as well-intentioned local ordinances create varying requirements that will be impossible to collectively meet.

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[1] See National Academies of Sciences, Engineering, and Medicine, 2018, *Assessing the Risks of Integrating Unmanned Aircraft Systems Into the National Airspace System*, The National Academies Press, Washington, D.C., https://doi.org/10.17226/25143.

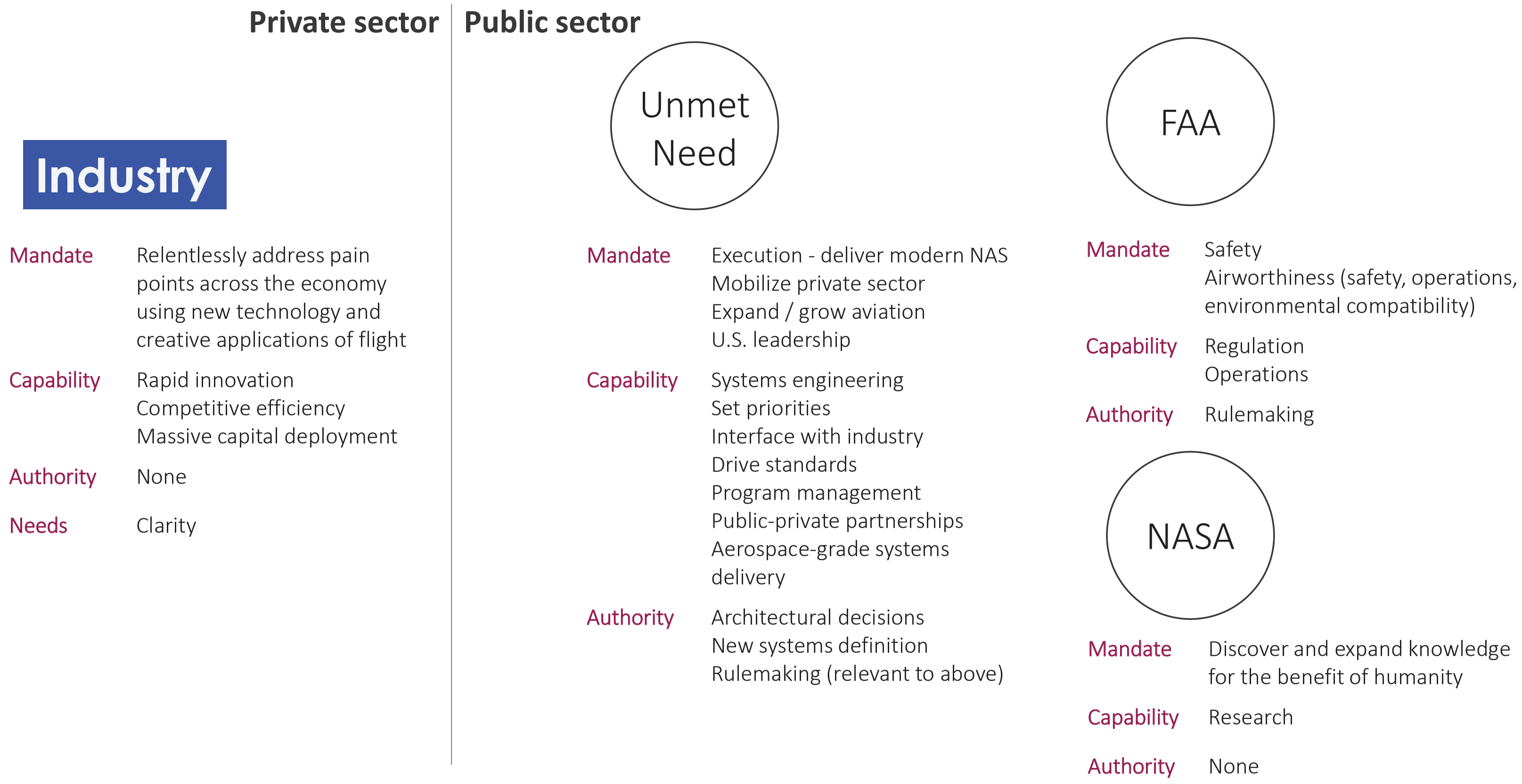


FIGURE 1.3 Gaps between industry and the government agencies involved in making advanced aerial mobility possible. NOTE: NAS, National Airspace System.

Private industry is working to close some of these gaps. But without an assigned government agency responsible for these areas, advanced aerial mobility could be impeded or fail to reach even a portion of its potential.

Adopting advanced aerial mobility in the United States is in the national interest, as is maintaining U.S. leadership in aerospace. A vision, and a way to achieve it, is crucial if the United States is to realize this goal. Beyond technical hurdles and system engineering, advanced aerial mobility will require addressing societal acceptance and policy issues related to privacy concerns, community preferences, airspace allocation, and land use considerations. Given the complex interdisciplinary nature of advanced aerial mobility and the gatekeeping role of regulation, planning and coordination for advanced aerial mobility has to take place at the federal level, with the aim of delivering the foundational decisions, standards, and regulations that enable the private sector to invest and deliver its innovations with clarity and confidence.

The long-term impacts of advanced aerial mobility on the economy and society could bring wide-ranging substantial benefits. The purpose of this study is to lay out that vision and is but a first small step that others will have to expand and build upon.

The vision for an expanded role of flight in society and the economy is not a new one but rather a long-standing goal from the early days of aviation—one hindered by the limitations of 20th century technology. In fact, from the day in 1927 that Charles Lindbergh landed the *Spirit of St. Louis* at Le Bourget in Paris, people have envisioned the potential of personalized flight to support on-demand movements of passengers and goods directly between locations.

At the time, Charles Lindbergh's crossing of the Atlantic was a pivotal moment, bringing a wave of capital, entrepreneurs, and engineers into the industry. Similar to today, a wave of innovation catalyzed many new businesses. Their shared vision was that soon everyone would be flying in aircraft at their own whim akin to using a car.

Aviation has come a long way since then, connecting the world, yet that vision has remained elusive. For nearly a century, flying for most people has been constrained to aggregation of passengers on long-distance, scheduled commercial air routes, with only enthusiasts or the wealthy undertaking the expense and complexities of private aviation.

This outcome was not expected. Progress during World War II raised expectations for a domestic revolution in the use of personal airplanes. Wartime advances in aircraft design and manufacturing, combined with the large number of trained pilots and people otherwise exposed to flight, fueled expectation that following the war there would be demand for hundreds of thousands of airplanes as the economy transitioned to peacetime growth. Indeed, industry responded, with manufacturers preparing themselves and the public for the coming new era in flight.

According to the General Aviation Manufacturer's Association, the general aviation industry sold a record high 33,254 aircraft in 1946, many of which were surplus World War II aircraft; however, the initial success did not last long. A contraction in aircraft sales came about suddenly thereafter. In 1947, aircraft sales dropped by half and declined further into the early 1950s. After a recovery in the 1960s and 1970s, general aviation aircraft shipments stalled again in the wake of product liability costs (see Figure 1.4).

Historical aircraft shipment data support the observation that general aviation failed to scale. The reasons behind this are numerous and interdependent. Operating small combustion-powered aircraft proved to be too expensive, and their complexity and consequent maintenance made them costly and unreliable. At the same time, piloting aircraft remained complex, with steep training requirements that held back growth in the pilot population. These forces limited scale and innovation and combined to keep aviation for personal transport beyond the reach of mass adoption. Ultimately, 20th century technology was not able to support a product that could scale into the needs of the personal aviation market (see Figure 1.5).

In contrast, commercial aviation thrived. Here, efficiencies could be gained through larger aircraft and complexity managed with highly trained professional pilots. Early regulated air service transitioned through deregulation and route structure and business model innovation. Today, as tens of thousands of people pass through mega-hub airports daily, one might wonder if personal aviation was a misguided idea or just before its time.

As discussed earlier in Chapter 1, technological advances in software and data, electric propulsion, sensors, and other areas are now spurring an entire industry to revisit this question. Technology is redefining flight, with software and data as critical elements of the advancements at hand. As firms apply these technologies to aircraft and the overall airspace system, they upend core assumptions around the aircraft, its economics, safety, usability, and the transportation systems in which it will operate.

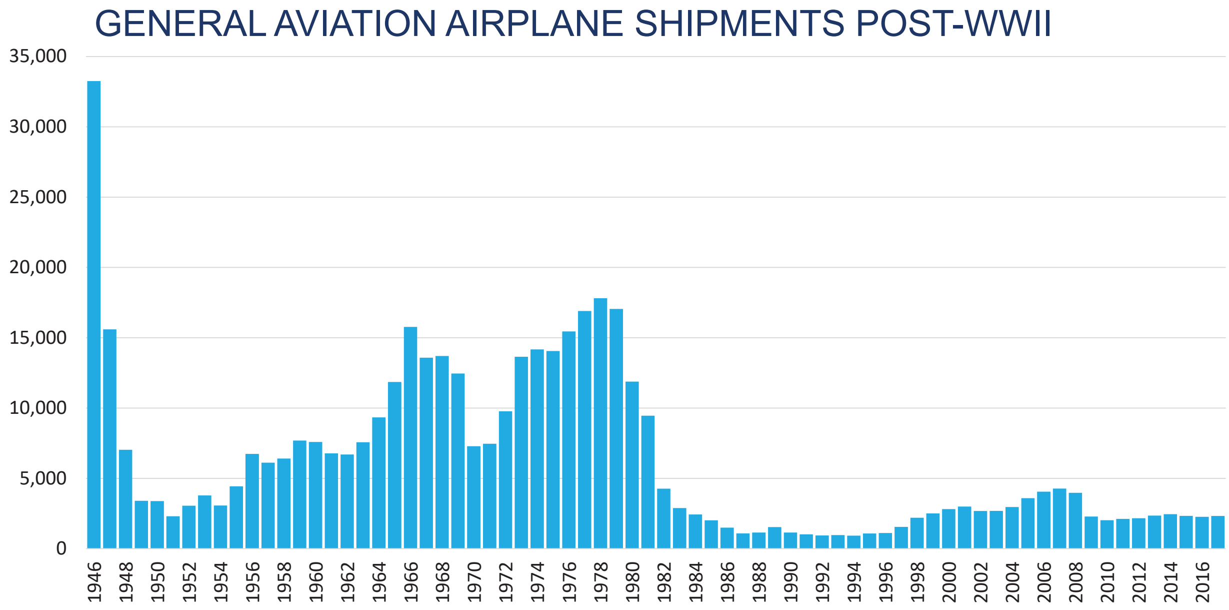


FIGURE 1.4 The general aviation market started out strong immediately after World War II, dropped significantly, recovered by the 1950s through 1970s, and then dropped substantially and never recovered. Graphic based upon data from the General Aviation Manufacturer's Association.

At present, the United States is potentially on the cusp of a revolution in transportation with long-term, far-reaching implications, from how people get across town to how to connect broader regions and move goods or provide essential services. The new capabilities that advanced aerial mobility delivers can significantly broaden the application of flight to drive productivity across the economy.

To understand the impact that truly accessible flight capability can have, it is helpful to understand that advanced aerial mobility represents the inclusion into this transportation mix of a mode that stands apart from

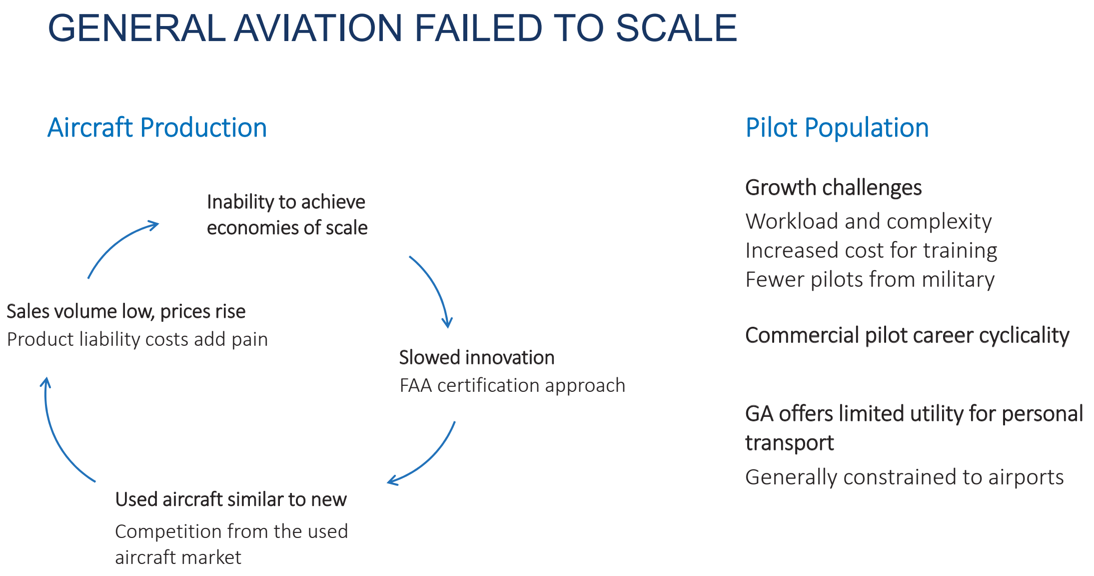
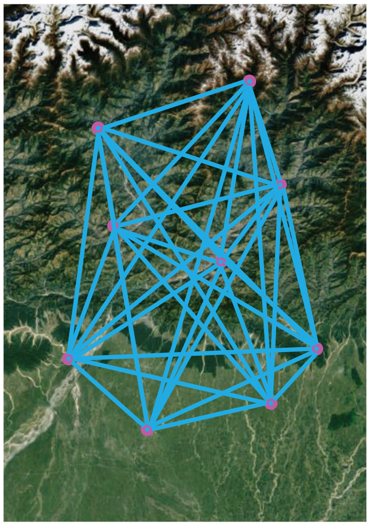


FIGURE 1.5 Factors in both the aircraft fleet and pilot population inhibited general aviation's progress and scale. NOTE: GA, general aviation.

AERIAL MOBILITY IS A NODAL TRANSPORTATION NETWORK



Inherent direct connectivity between every point

No path infrastructure to build and maintain

Flexible capacity

Resilient to disruption

Small footprint

Easier to overlay into already developed areas

FIGURE 1.6 Advanced aerial mobility can directly connect all points, with no physical path infrastructure to build or maintain. In place of physical path infrastructure, advanced aerial mobility networks will employ inherently flexible infrastructure including air traffic control and flight path design.

today's infrastructure intensive networks. Aerial mobility is a nodal transportation network in contrast to road and rail, which are linear networks. The flexibility, resilience, and low resource intensity of nodal networks are key strengths and, as evidenced by water transport throughout history, have proven value (see Figure 1.6).

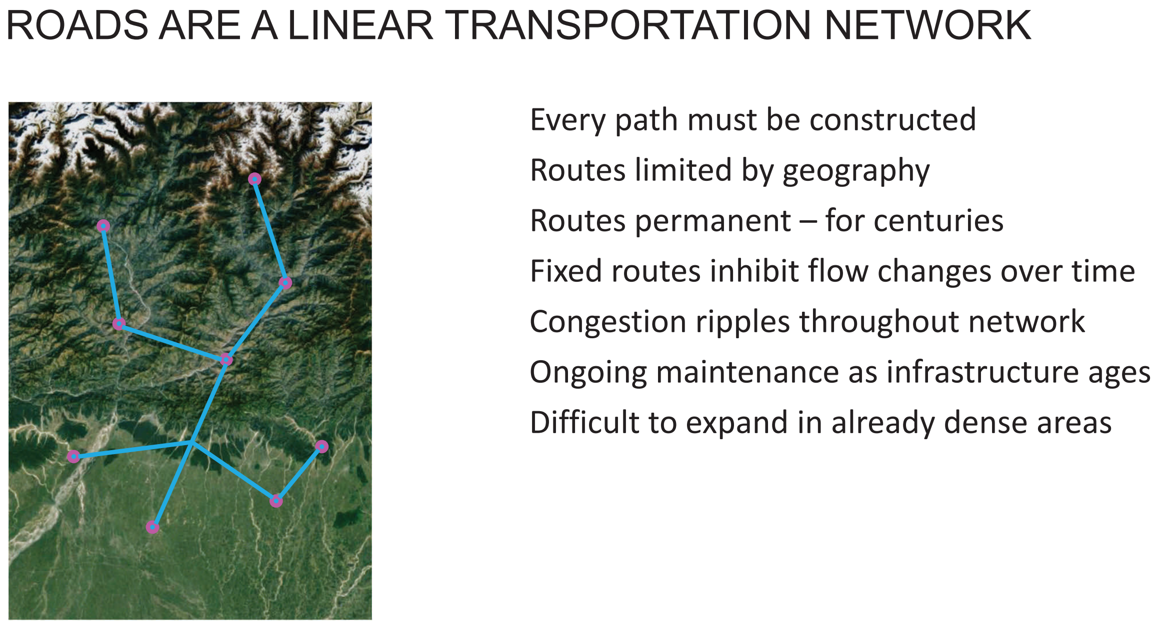
As advanced aerial mobility matures and is deployed, each application has the potential to bring profound impact, because it represents the inclusion into the transportation mix of a nodal network—a transportation mode that is not limited to linear physical path infrastructure (e.g., roads and rails) and that does not depend on building and maintaining extensive infrastructure to sustain or expand service capacity over time.

The current commercial air transport system is a nodal network; however, an advanced aerial mobility network will have some differences. Such a network is a more complex and multidimensional space than the current air traffic system, which has legacy attributes of static routes. At its most basic form, it includes many more nodes, not all of which are fixed (e.g., drones taking off and landing on delivery trucks). It is inherently far more complex when displayed visually but can have many advantageous attributes, such as flexible capacity and resilience to disruption, among others. While the advantages to a nodal network are clear, it must be recognized that the nature of airspace management may require a level of flexibility to route structure based on variables such as weather, security concerns, and other stakeholder activity in the airspace volume. Further, as megacities scale, their area increases—providing a fundamental challenge to linear, path-based networks.

In contrast, major transportation networks such as roads and rail are linear. They must be built and maintained. Routes are fixed and limited in capacity. They make a permanent imprint on the landscape, influencing future behavior for centuries. In linear networks, a single vehicle can cause congestion, and these effects can ripple through the networks (see Figure 1.7).

Today, the nodal networks of ocean transport and commercial air travel serve only narrow use cases within the overall transportation systems. The modern world runs primarily on roads and rail, particularly for short to medium journeys.

The consequences of modern society's transportation dependence on linear networks are growing ever more apparent. Megacity regions push the limits of road scale and congestion. Infrastructure becomes costlier to maintain with age. In the United States, infrastructure is deteriorating yet combined spending to maintain road networks



ROADS ARE A LINEAR TRANSPORTATION NETWORK

- Every path must be constructed
- Routes limited by geography
- Routes permanent – for centuries
- Fixed routes inhibit flow changes over time
- Congestion ripples throughout network
- Ongoing maintenance as infrastructure ages
- Difficult to expand in already dense areas

FIGURE 1.7 Roads and railways are inherently limiting in how they connect multiple points. They cannot directly connect as many different locations, they cannot flex to new movement patterns, and maintenance costs can mount over time.

exceeds $145 billion annually.[2] Increased roadway congestion results in billions of dollars of lost productivity, and ongoing maintenance costs inhibit road expansion, particularly in dense urban areas. In contrast, the $4.1 billion runways and related airfield infrastructure (excluding terminal and amenities) cost of air transportation is indicative of its high efficiency.

Advanced aerial mobility development will evolve in response to technical, regulatory, and economic factors, generally taking the path of overall least resistance as the private and public sectors work in their respective roles to facilitate progress. Where it is found to be feasible and economically attractive, innovators can create a lightweight transportation capability that delivers benefits quickly and effectively introduces a thin overlay of high-speed flexible transport, complementing existing linear networks. These early applications become the seeds of a modern nodal network. With this, the community builds experience in overcoming the technical, regulatory, and societal hurdles required for future larger-scale implementation.

A nodal aerial transportation network represents a fundamental step forward for transportation and society. As a complement to linear networks, it allows separation of high-priority movements such as medical emergencies and disaster relief onto a resilient high-speed network not subject to disruption on the ground. With operating experience, the scale and use cases expand dramatically.

It is very difficult to define how new capabilities in flight will be put to use ex ante. A fundamentally new capability in flight implies an expansion of creative uses to drive productivity across the broader economy. Within advanced aerial mobility, the potential uses, configurations, and operating models are numerous and highly diverse. In setting a path toward a national vision for advanced aerial mobility, acceptance of this fact is important. Any vision must first address safety, but it must also accommodate scale, mitigate potential impacts, and build in flexibility to enable new and unforeseen applications to unfold.

Pursuing this vision to establish and maintain U.S. leadership in this new capability is in the national interest. However, aerial mobility systems will not self-assemble out of the private sector. Both private and federal investment in research and development supporting the development of standards and regulations throughout the aerospace ecosystem will play an important role.

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[2] U.S. Department of Transportation, Bureau of Transportation Statistics, 2017.

2

A National Vision for Advanced Aerial Mobility

As technology progresses to simplify and ultimately expand access to flight and, more broadly, to vertical space for movement, it leads to adoption of flight into many new applications for which it was not previously suitable. These new applications will touch industries across the economy—some of which are being studied and planned for today, and many of which will be unforeseen and discovered by creative entrepreneurs.

With predictions that more than 65 percent of the world's population will live in urban areas by 2050,[1] demand calls for transportation modalities that can effectively serve the expanding urban and exurban market. This has implications for citizens' quality of life as well as public services and commerce. Inadequate ground-based infrastructure supporting traditional mobility in and around cities could result in a $1.2 trillion national loss of gross domestic product by 2025,[2] with commute times topping 90 minutes or more.

In the longer term, the second-order effects of advanced aerial mobility will impact real estate, land use and city planning, and numerous facets of modern society. This is not a new dynamic but a continuation of a centuries-long relationship wherein transportation shapes spheres of movement, interactions with others, ideas and opportunities and outlooks on society and the world. As such, developing a national vision for advanced aerial mobility, and a plan to execute and achieve it, is squarely in the national interest. The United States stands to benefit both by preparing for its adoption and by moving now to promote U.S. leadership in the technology and systems for this new industry as it builds out worldwide.

BASIS FOR THE VISION

The national vision for advanced aerial mobility is based on several key findings and concepts reviewed throughout this study:

- Regulation for safety is inherent in the National Airspace System. It plays a necessary role in design, standardization, and operation of the National Airspace System.

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[1] U.S. Department of Transportation, "Smart City Challenge" (2016); Texas A&M Transportation Institute, 2015 Urban Mobility Report; Smart Cities Council, "Smart Cities Readiness Guide"; TomTom Traffic Index (2014); World Economic Forum, Strategic Infrastructure report; Deloitte Analysis.

[2] U.S. Department of Transportation, "Smart City Challenge."

- Safety is the highest priority consideration driving the design and planning of advanced aerial mobility system, and of integrating new technologies into the National Airspace System. Safety manifests in technical, regulatory, and societal acceptance issues throughout this space.
- Societal acceptance of advanced aerial mobility is a key factor driving the design and rollout of any advanced aerial mobility system. Acceptance of safety is key, but many other factors beyond the technical attributes of the system will drive how the public perceives, accepts, and adopts advanced aerial mobility. Strategically addressing the health and welfare, including psychoacoustic effects, of vehicle noise up front is a critical element for societal acceptance. Addressing privacy concerns is also key.
- The committee envisions that this will be a very complex system. The nation needs an organized and coordinated plan if it is to develop. A complex system-of-systems of this type will not self-assemble out of uncoordinated efforts.
- Cyber-physical security plays a critical role in the safety and resilience of any advanced aerial mobility system. Achieving cyber-physical security will require new methods, and it will have to be implemented throughout the system in order to support actual security as well as to build public trust in advanced aerial mobility. Public trust in autonomous systems involves security as well as transparency for the public, and this will be a pervasive theme as more autonomous systems (e.g., air, ground, and other) deploy in society.
- There is a reinforcing feedback loop of technology development and real-world flight experience as well as learning from applied operational experiences that is key to the progress of the vision.
- The possibilities of advanced aerial mobility extend beyond just urban air mobility (UAM) and while UAM will be a very large and attractive application and market, there are many useful stepping-stone applications that serve as important precursors to developing the sophisticated capabilities and industry maturation required to implement high-scale UAM.
- Infrastructure plays a key role in advanced aerial mobility deployments. The diverse new applications it will spawn mean new infrastructure—in some cases, infrastructure specific to the application. This infrastructure in many cases will be embedded with technology and connected into networks. This requires standards and partnerships with the private sector, as well as coordination across federal, state, and local bodies to ensure uniformity of regulation. Current standards have gaps and will need to be enhanced.
- Innovation and capital will take the path of least resistance, and industry can act quickly but only in response to clarity from regulators. This path of least resistance means identifying opportunities leading to an acceptable return on investment in the least amount of time. If regulation resists or restricts innovation, investors will not engage. If offshore opportunities motivate investment, it will be valuable to know that and encourage regulators to reassess how they are restricting development and deployment of advanced aerial mobility.
- Regulators and private industry play crucial roles, and these will have to evolve in the face of a new mission versus the orientation of the past 60 years of air mobility, which focused on ensuring safety in a gradually evolving National Airspace System dominated by commercial air travel.
- As new capabilities and flight operations are defined and permitted, private industry will develop technologies and products to fulfill them and will rapidly drive their application into numerous unforeseen areas where they create value. The operational experience gained from the applications and the resulting capabilities built throughout the supply chain and manufacturing base will feed into defining and meeting the demands of the next level of operational complexity, automation, and scale, which, in turn, will be developed and exploited by the private sector as the cycle repeats. However, succeeding in establishing this cycle requires a change in mandate, capabilities, and authority on the public sector side as well as more effective engagement with the private sector.

Recommendation: In order to formulate a U.S. Joint Advanced Aerial Mobility Master Plan, NASA and FAA should form a partnership to manage responsibility and accountability across the various stakeholders to participate in the development of the Master Plan.

THE GAPS AND BARRIERS INVOLVED IN ACHIEVING THE VISION

There are many challenges that will have to be overcome to achieve the full potential that advanced aerial mobility technology offers. At the highest level, these challenges stem from the fact that the airspace system in its present form was not designed to accommodate the density levels and automated operations needed to make advanced aerial mobility viable.

In Chapter 1, success in achieving the advanced aerial mobility vision was framed as addressing a series of factors, including intrinsic aspects of the system such as safety, regulations, scalability, flexibility, and resilience, as well as aspects that take into account the externalities of environmental responsibility and societal acceptance. These factors are expanded upon in this chapter under a construct that considers the gaps in system characteristics of the airspace system today versus what it will need to evolve into, as well as barriers to achieving the vision and coordinating all stakeholders to define, develop, and deploy a very complex system-of-systems.

Early applications of advanced aerial mobility, such as those operating with less complexity, at lower density, and in more remote areas, will likely face fewer of the challenges outlined below. However, the most demanding applications such as highly automated, high-density UAM operations will emerge as the result of overcoming these challenges.

Gaps in System Characteristics

The success of advanced aerial mobility depends on introducing a new level of capability into the National Airspace System, including the airspace itself, communications methods, air traffic management (ATM) supporting high traffic density, integration of autonomous flight operations, and new types of infrastructure. All of these advancements will have to work alongside and integrate seamlessly with today's manned commercial and general aviation air operations.

The committee noted a number of technical challenges, which impact safety, scalability, resilience, and other areas. Some of the specific aspects to focus on include the following.

Safety

Advanced aerial mobility must demonstrate the high safety levels expected by the public for modern air transportation systems. Safety in today's National Airspace System is very high for commercial air travel. However, the smaller airplanes and rotorcraft in the general aviation fleet trail commercial aviation in safety, with a fatality rate that exceeds automobile travel (on the basis of passenger miles traveled). Many of the causes of fatalities in general aviation are operational and are due to human factors or inherent vulnerabilities of legacy aircraft such as their age. The ultimate goal for new systems is the best possible safety, and the committee does not believe that advanced air mobility systems that only achieve general aviation safety rates will be viable.

Safety management in the National Airspace System today builds margin around these vulnerabilities. Placing trained humans in the loop to manage safety and building in procedural safeguards such as traffic spacing requirements are both examples. Advanced aerial mobility introduces several underlying changes that correspondingly require new methods to be brought to bear in the approach to safety. Electric propulsion and increasing levels of automation may reduce the instances of certain causal factors but increase instances of other factors or introduce new causes altogether. Similarly, new technology introduced in ATM may experience a similar effect. The system-wide-level complexity of an airspace system supporting advanced aerial mobility can introduce unforeseen interactions that create new hazards to plan for and mitigate. Safely implementing this new capability in the airspace system will first require gaining experience in a low-risk environment and gathering data with which to learn and improve.

Security

Security is already a high priority in today's airspace system, but the approach and technologies employed will need to change and expand their footprint as advanced aerial mobility systems are scaled. The committee heard from experts who highlighted the security gap around the need to prevent disruption to operations via attacks on digital communications links, the data that flows over them, or satellite-based positioning systems. Aspects of security today that are based on trust between humans such as voice communications between pilots and air traffic control (ATC) will need to be approached differently as digital links proliferate and potential points of attack from the cyber realm are introduced. Technology gaps also exist with respect to safely managing fallback navigation methods for autonomous systems in the event of global navigation satellite system outages or spoofing.

The committee did not focus on other areas of system-wide security for specific applications such as UAM, including security at vertiports or for air taxi passengers in flight, but acknowledges needed attention in these areas.

Resilience

Resilience of a system is a measure of the ability to recover quickly from random or intentional disruptions while maintaining an appropriate degree of functionality. Fault Tolerance and Recoverability in today's National Airspace System is based on a combination of redundant systems in aircraft and throughout the flight environment, as well as processes that rely on trained humans to respond to contingencies. Thus, fault tolerance and recoverability today are handled in some cases through design of systems and in other cases through operational procedures.

Similarly, advanced aerial mobility systems must be able to maintain required minimal functionality when components of the system suffer degradation or outage and have the ability to efficiently recover from contingency events or situations. This applies both at the vehicle level and across the airspace and throughout mobility systems where degradation in one part can have knock-on effects elsewhere.

In the initial implementations, the approach will be similar to today, through design of redundant systems as well as processes with humans in the loop to cover various functions throughout the system. However, as scale and complexity increase, this capability will increasingly need to be handled by systems designed for the task as scale and complexity pass thresholds exceeding the ability for humans to intervene directly. Collection, analysis, and dissemination of sound system reliability data will play an important supporting role here. Additionally, it will be important to consider security and human factor aspects in any potential solutions.

Communications

The majority of current communications between aircraft and ATC use voice spoken over VHF radio frequencies. Among the other forms of safety-critical communication in the National Airspace System is information exchanged between aircraft and traffic management systems through radar and transponders, as well as through transponders that communicate directly between aircraft in certain circumstances.

New communication methods are needed to support greater scale and also to support the requirements of unmanned or autonomous aircraft. The committee heard several proposed methods and communications standards that could meet this need. However, consensus around a method or set of methods to focus on has not been reached, nor has agreement been reached on which methods would be considered safety-critical under either nominal or off-nominal conditions. Depending on the application, differing views remain as to the order of communication, such as whether or when vehicles would communicate directly with each other or circumstances when all communication would be with a centralized traffic management system.

Uncertainty also persists with respect to the physical layer for communications links, with options ranging from LTE and 5G networks to satellite links, as well as purpose-built radio frequency links using either licensed or unlicensed portions of the frequency spectrum. Today, there is no globally accepted spectrum for autonomous system command and control. The development of standardized command nonpayload communication capability has been stymied as a result. Overall, a lack of a globally accepted communications architecture is a key gap to solve for and has follow-on impacts for choices and design around ATM solutions for advanced aerial mobility, including autonomous systems.

Integration of Autonomy into the Airspace System

Current airspace configuration, operational rules, and procedures did not anticipate the emergence of an autonomous aviation ecosystem. Introducing autonomous air vehicles carrying freight or passengers alongside manned aviation operations is highly complex. From a design standpoint, vehicles incorporating increasingly automated software capabilities will have to be designed, developed, and certified. Closely interlinked with design aspects, operations will have to be defined and procedures for the airspace system created to work with autonomous flight. These efforts require precise coordination and agreement on the exact overall capabilities the efforts are directed toward.

Current challenges to integrating autonomy into the airspace system include further research and development of core technologies as well as systems engineering to integrate the different components into a system that is fieldable and able to support flight testing. Among the many examples of gaps within this field is the lack of detect and avoid capability, or the ability of the autonomous vehicle to remain "well clear" of other users of the airspace so as to not create a collision hazard that impacts safety. The committee heard that the defense community has made substantial progress in these capabilities in recent years and is a potential source of relevant technology transfer.

At present, operation of autonomous vehicles is generally relegated to segregated airspace volumes and over the most rural areas. The expectation is for introduction to continue in line with a trend that introduces new capabilities with respect to the overall risk profile that these operations present, initially favoring lower risk operations—for example, over sparsely populated areas. We envision the future air traffic system as having all classes of vehicles sharing principally the same airspace and that airways, approach routes, and technology will sort the traffic out and prevent conflicts. Ultimately, routine "file and fly" access—the ability to operate "at will" without the need for one-off special approval for each operation—to all classes of airspace, subject to constraints of airspace design and airspace use by other traffic, is essential to the success of later applications of advanced aerial mobility.

Scalability

The scale of activity in the National Airspace System, at least with respect to commercial airline operations, has grown substantially over recent decades. The scalability of the National Airspace System is closely related to the density of operations it can support, and technological advances in traffic management, precision flight path following, and new procedures have increased the tempo of operations in the terminal area around large airports as well as in the en route structure. However, a major limiting factor in scalability remains the limitations of human operators throughout the system to safely manage the demands of handling additional density.

Overcoming these limits necessarily involves increasingly replacing human responsibilities in these roles with automation. This is a complex undertaking, as detailed in this report's coverage of the challenges around autonomy, and involves technical, systems engineering, and human factors, among other considerations, in order to succeed. The expectation is that early applications of advanced aerial mobility will thus work within the scale limitations of today's National Airspace System. However, a successful approach to advanced air mobility must have the capability to scale as markets for various applications emerge and grow. Technologies, operational procedures, and adjacent services will have to be flexible and capable to grow from the current levels of today to a robust global ecosystem.

Flexibility

Today's airspace system is designed around very defined and well-understood flight operations and air vehicle types. The dominant mission types flown in the national airspace have remained relatively static over recent decades. Advanced aerial mobility fundamentally expands the viable applications for flight, and many of these applications remain unforeseen.

Flexibility is critical as new use cases are tried and tested and as operational concepts emerge. As new technologies are developed, changes to the system must integrate them such that maximum economic benefit can be realized without compromising safety or environmental responsibility. A flexible advanced air mobility system will include a need for flight rules and procedures for routine operation in all classes of airspace as well as for ground operations.

Infrastructure

Surface infrastructure to support aviation is built around the aircraft currently in the airspace, predominantly airplanes and helicopters. The majority of journeys are intercity trips of distances longer than what is convenient via automobile. Today's air transportation mobility system is physically partitioned from other modes of transport, with passengers passing into and out of this system through highly controlled structures at airports and with the air-side of the infrastructure thoroughly segmented away from all external factors.

Likewise, the route structure, navigation aids, and approach and departure procedures are designed with today's aircraft and travel patterns as assumptions. For example, airways and terminal approach procedures are designed for longer routes and do not support or envision short urban flights. Instrument routes for flights in inclement weather send aircraft on long roundabout routes and often require higher minimum altitudes than would be usable or practical for advanced aerial mobility vehicles on short urban trips.

Advanced aerial mobility, with its vehicle types ranging from small parcel delivery drones to larger cargo and passenger vehicles and with its different and varying movement patterns, presents significant changes to the types of infrastructure that will support it. More ground locations may be served using advanced aerial mobility systems than with airports today. These ground locations will be smaller and far more numerous than airports and will necessarily be more seamlessly combined with other transportation modes and in closer proximity to the general public, less able to partition and segment.

Yet today's airports may see increased activity and undergo changes to optimize around new advanced aerial mobility traffic flows. Trip distances, routes, and altitudes will likely vary significantly from aviation today. Among the many configurations to explore for various applications, a common aspect is that a scalable system will be dependent on design and standards for ground infrastructure (e.g., vertiport design and spacing) and the ways that infrastructure connects and interfaces with the rest of the National Airspace System.

Financing for air transportation infrastructure is well-established, combining a mix of public and private sources to address both the airside (e.g., runways) and terminal-side (e.g., gates, concourses, etc.) for airports. Similar financing will evolve for new advanced aerial mobility infrastructure but will likely have different requirements and needs for support.

Airspace and Flight Data

For operations, there is a need for flight data gathering and dissemination specific to autonomous system operations, including microweather forecasting and reporting.

Air Vehicles

The committee did not focus on vehicles per se. However, propulsion system limitations were noted, including battery and hybrid technology options and recharging infrastructure. The recharging requirements will place demands on local infrastructure, although currently electric ground vehicles are placing demands on infrastructure and will continue to do so, providing an experience and industrial base that could benefit electric-powered aerial systems.

Barriers to Executing the Vision

The barriers to executing the vision relate to the coordination required in order to introduce innovation into the National Airspace System in a way that preserves safety and addresses the needs of all stakeholders. Given the increasing complexity of operations envisioned in the National Airspace System as well as the pace of innovation across the many disciplines relevant to advanced aerial mobility, this coordination is instrumental in determining the pace of realizing the vision for advanced aerial mobility and the ultimate success it is likely to achieve. Some examples of these barriers are discussed below.

Collaboration

Advanced air mobility is a multidisciplinary challenge. The system-level complexities are daunting in many respects. Overcoming the hurdles will require collaboration between stakeholders from across different areas of specialty, both within and outside traditional aviation. No single entity will solve all the issues ahead. Government and private sectors will have to coordinate closely to enable each other and to achieve progress.

Societal Acceptance

Aside from safety, one of the most important barriers to adoption of advanced aerial mobility applications and services is societal acceptance of this new technology and perception that the benefits it delivers outweigh the impacts it has on bystanders, the environment, and overall quality of life. The public's perception of the various contributing factors to acceptance is as important as the factors themselves, and the interplay between them is very complex and can be subjective in certain circumstances. Environmental factors such as noise and visual annoyance from air vehicles to perceptions about privacy and a sense of trust in these new systems are all very important to plan for accordingly.

Studies conducted by Booz Allen Hamilton yielded some interesting data related to passenger acceptance and expectations.[3] There is a perceived concern from the public about ride sharing in an aircraft with other unknown individuals. Survey data show public reticence to the idea of flying without an onboard pilot. There were overall personal security and privacy concerns among potential users of advanced air mobility.

The public brings preconceived notions about aspects of advanced aerial mobility that are important to consider. Noise and annoyance from commercial airliners or consumer drones disturbing the peace for beachgoers may be the baseline experiences for forming perceptions about advanced aerial mobility services that remain only in the planning phase today.

Debates over privacy have impacted progress in early applications, including drones. The number of state and local regulations in play have imposed a "patchwork quilt" of limitations and prohibitions, making expansion of advanced aerial mobility difficult.

Over time, the benefits to the public in overall cost and time savings as well as greater productivity and convenience could help overcome many of these concerns. However, they do need to be addressed upfront and in a purposeful coordinated way.

Regulations

There are several barriers to executing on the vision that relate to the regulatory function. Regulations play an integral role in coordinating, standardizing, and ensuring safety throughout all parts of the National Airspace System. In the gradually evolving National Airspace System of the past 60 years that has supported the relatively static dominant application of commercial aviation, the existing regulatory function has succeeded in driving exceptional safety and improving efficiency.

Primum non nucere (first, do no harm) is the mantra of regulators across the globe. Regulators will want technology developed to support advanced air mobility to be compliant with all current and foreseeable future regulations and meet universally accepted performance criteria. But beyond this, advanced aerial mobility brings changes to the assumptions under which today's regulatory function evolved and with it requires a new way that the regulatory function must work.

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[3] Booz Allen Hamilton, 2018, *Final Report: Urban Air Mobility (UAM) Market Study*, submitted to NASA on November 21, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190001472.pdf.

Regulations will have to change to accommodate a new wave of innovation in aviation. New technologies must find a way to be certified. New, diverse, and constantly evolving applications of flight will displace the gradual evolution of commercial aviation. Flight will take place between highly granular destinations and over short distances that were never before considered economically or technically feasible.

Many changes are required to enable this, but regulations are notoriously difficult to change and implement. It is not uncommon for a decade or longer to pass before a new rule or requirement is adopted. Regulators are working around this by adopting a posture of risk-based approval for certain unmanned operations while operating within the current regulatory framework. The major concern is that at present, the risk cannot be determined for non-stochastic processes and designs that are new and have no historical basis.

These changes to enable advanced aerial mobility cannot occur on their own and cannot be accomplished by a single party—not even a regulator with the authority to do so. The recent rewrite of the Federal Aviation Regulations Part 23 certification rules is an example, bringing together regulators, industry and trade associations, standards development organizations, and others to complete it.[4] Experience, data, and coordination between the public and private sectors are critical requirements to enacting change, and standardization plays a central role. The mandate within the public sector and regulatory function to pursue the technological progress that comes with advanced aerial mobility is the single most critical enabler to successful execution.

With respect to aircraft certification, this is one existing capability area that transfers well into the future requirements. However, changing flight standards or airspace architecture is a wholly different undertaking.

The large number of new entrants is notable in that a variety of firms are offering aircraft concepts targeting the advanced aerial mobility market. Many of these have never certified an aircraft for commercial (i.e., passenger or cargo) transportation. A new certification construct could greatly improve advanced air mobility market participation by these new, especially non-aviation, entrants, though it must be designed so that current safety standards are maintained within these new platforms.

The NASA UAM National Campaign program is a step in the right direction, especially the objective to "Accelerate Certification and Approval. Develop and assess an integrated approach to vehicle certification and operational approval."[5] This is especially important because the introduction of a new safety risk can stem from the vehicle design as well as the way in which it is being operated in the airspace.

Environment

The committee received information from the FAA showing that, in some cases, noise and other environmental concerns had delayed or totally prevented implementation of the Next Generation Air Transportation System (NextGen) needed to modernize U.S. air transportation. It was clear that noise concerns, founded on health and welfare impacts, are complex psychoacoustic issues. It is important to understand the direct environmental impact characteristics of advanced air mobility vehicles. It is just as important to understand the public reaction to these technologies.

Several presenters provided evidence about the importance of community outreach when implementing new aviation capabilities. Being able to communicate a vision that squarely addresses societal benefits is critical to successful implementations of advanced air mobility. The committee was briefed by several organizations on studies on the potential benefits and market size of implementing advanced air mobility. While elements of a compelling vision were evident, the assumptions were not always realistic, and the ability to accurately model the costs and benefits was not clear. Having a clear understanding of societal effects will enhance community outreach and help lessen the barriers to advanced air mobility implementation.

Finding: While certification of advanced air mobility vehicles and integration into the airspace system will be challenging, there are additional barriers to consider. Public acceptance of advanced air mobility, particularly noise

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[4] Part 23 establishes airworthiness standards for normal, utility, acrobatic, and commuter category airplanes.

[5] See "UAM Coordination and Assessment Team (UCAT), NASA UAM Update for ARTR." Presentation by NASA to the committee, May 22, 2019, p. 18. (Note: ARTR refers to the Academies' NASA Aeronautics Research and Technology Roundtable.)

aspects, is perhaps one of the biggest challenges along with safety. Failure to address these issues could hinder advanced air mobility implementation.

Finding: Noise from aircraft, and other transportation modes, is a complex topic spanning acoustics, the physiological way humans experience noise, and the psychological perceptions listeners have of the source of the noise and what it represents to them. A large body of research spanning this area has been conducted over the past century, with learning outcomes relevant to modern aviation.[6] Admittedly, noise from advanced aerial mobility vehicles will be different from noise from commercial aircraft or helicopters. Many of these vehicles will be powered by electric motors, which will be inherently quieter than jet engines or rotorcraft. However, aircraft noise originates from many sources including aerodynamic sources, propeller or rotor blades, and the complex and highly dynamic interactions between these. Electric propulsion does enable new propulsion possibilities that promise to change the character of aircraft noise and to reduce it overall. The degree to which this falls below the public's threshold for annoyance remains to be determined and depends on additional operational and contextual factors. Annoyance caused by noise is not strictly related to noise levels. "New noise"—that is, noise in places where there was no noise before—causes high levels of annoyance to the public that experiences it. So it is to be expected that the introduction of advanced aerial mobility vehicles will lead to annoyance and adverse health and welfare effects. Understanding the nature of these effects is critical to successfully mitigate them.

Finding: Early applications of enhanced aerial mobility may include operations with a less intense acoustical impact on bystanders (e.g., less frequent operations in rural areas) and with strong positive social impact (e.g., emergency medical services, search and rescue, and disaster relief). These applications can be a valuable test bed to learn and refine low-noise operations as well as to actively shape positive public perception of the technology.

Finding: Advanced aerial mobility can bring about transformation in a number of industries (transportation, emergency response, and cargo/package logistics). However, it is important to ensure that societal benefits and costs of advanced aerial mobility implementation are well understood using scenario-based analyses to assist, as all the applications will most likely not be evident until deployment is under way and users adapt to new capabilities. Being able to communicate benefits will aid in public acceptance and community outreach.

Recommendation: Research should be performed to quantify and mitigate public annoyance due to noise, including psychoacoustic and health aspects, from different types of advanced aerial mobility operations. NASA should facilitate a collaboration between relevant government agencies—including FAA, Department of Defense, National Institutes of Health, academia, state and local governments, industry, original equipment manufacturers, operators, and nonprofit organizations—to prioritize and conduct the research, with responsibility allocated per a coordinated plan and accountability for delivery incorporated. The research should be completed in 2 years.

Recommendation: NASA should facilitate a collaboration with other relevant government agencies—the FAA, Department of Commerce, and Environmental Protection Agency—and industry—original equipment manufacturers and operators as well as academia and nonprofit organizations—to conduct scenario-based studies to assess societal impacts (e.g., privacy, intrusion, public health and welfare, transparency, environmental, inequity) of advanced aerial mobility vehicles and associated infrastructure. These studies should recommend a path to implementation that prioritizes maximum public benefits.

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[6] See M. Basner, C. Clark, A. Hansell, J.I. Hileman, S. Janssen, K. Shepherd, and V. Sparrow, 2017, Aviation noise impacts: State of the science, *Noise Health* 19(87):41-50. See, generally, the Pennsylvania State University website "NoiseQuest" at https://www.noisequest.psu.edu/. See, for example, National Research Council, 2002, *For Greener Skies: Reducing Environmental Impacts of Aviation*, The National Academies Press, Washington, D.C., https://doi.org/10.17226/10353.

FIGURE 2.1 Self-flying air taxi from Joby Aviation. It represents an example of a potential future air taxi vehicle. SOURCE: Joby Aviation's Aircraft in Santa Cruz, Calif., Joby Aviation, 2019.

Economy

Most, if not all, of the economic concerns relate to the scalability of advanced aerial mobility operations. Business case closure will be largely dependent on the cost associated with solving the aforementioned barriers and bringing cost to the consumer in line with traditional modes of ground-based transportation or by creating value with respect to the new locations it can uniquely serve or the time it can save. The value delivered to the consumer by utilizing advanced aerial mobility, whether it be for simple package delivery or point-to-point personal transportation, will define acceptance and economic viability. Value per seat-mile or freight cost per mile will be the metric by which businesses will be built. For air taxi operations, current estimates of per-seat mile cost for a two-person aircraft (like the example in Figure 2.1) average approximately $11 per mile.[7] Early versions of air taxi operations using a five-seat electrically powered vertical takeoff and landing (eVTOL) air vehicle have an estimated cost of approximately $6.25 per mile.[8] These costs are presently higher than a luxury car ride share. If the time savings to the consumer has value, the higher cost may be acceptable.

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[7] Booz Allen Hamilton, 2018, *Final Report: Urban Air Mobility (UAM) Market Study*, submitted to NASA on November 21, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190001472.pdf; McKinsey & Company, 2019, *Urban Air Mobility (UAM) Market Study*, submitted to NASA in November.

[8] Ibid.

ACHIEVING THE VISION

The gaps and barriers outlined above address the differences between the National Airspace System today and what the community envisions it potentially evolving to in the long term. Taken as a whole, these challenges can appear dauntingly difficult to surmount from today's perspective. The technologies that must be proven and integrated, the system-level considerations and input from stakeholders that are required, the coordination across public and private sectors, and the operational experimentation and buildup of experience that will inform the optimal working of the future National Airspace System can make it difficult to identify and agree on a starting point to begin moving forward.

Finding: It is important to consider a phased, iterative approach to development, testing, and introduction of new capabilities. It is not reasonable for a system of this degree of multidisciplinary complexity, with as many stakeholders involved (including the general public) and with regulatory involvement at every step, to self-assemble out of a mass of uncoordinated innovation efforts. Rather, coordination leading to interoperability and standards is essential.

The committee heard evidence to believe that viable applications of the technology and airspace system capability can likely be exploited even at the increments that are introduced. These incremental capabilities are directly constructive toward the systems required for UAM and the sooner they are fielded, the sooner experience with them is gained and further capability can then be introduced. The approach should, however, be flexible to react to and accommodate entrepreneurial advances that bring advanced capability faster than anticipated.

If a well-thought-out strategy is created to approach these challenges and break them down into more manageable pieces, then a coordinated effort is more easily achieved and several benefits result from easier coordination of stakeholders and standards development through to collaboration with regulators and the benefit of experience gained at each step to inform the next. However, for this approach to succeed, it must balance the need to coordinate around an organized plan with the need to be flexible to entrepreneurial approaches producing unexpected leaps forward in capability.

As a roadmap is created to guide coordinated efforts to overcome the gaps and barriers, due consideration should be given to defining each milestone such that it supports meaningful and usable new capabilities in the National Airspace System and that it generates practical data, experience, capability, and insights that inform the next milestone. Guiding priorities at each milestone should include safety, environmental responsibility, societal acceptance, flexibility, scalability, and open access.

Working Together

The committee envisions a National Airspace System that continues to evolve as a system of systems. Its complexity, the diverse and evolving applications it will support, and its multidisciplinary nature means that its structure favors a modular and standards-driven architecture rather than being designed and built as a monolith. This is further reinforced because enhancements to the National Airspace System necessarily require development by stakeholders across the private and public sectors. As such, it must evolve on the back of standards that support coordination across stakeholders. Standards also serve to support future expansion of capability and growth while managing and encapsulating complexity.

The private sector possesses the resources, capital, and capability to execute on addressing the challenges posed by implementation of advanced aerial mobility at increasing levels of complexity and density. The private sector will have to be mobilized to deliver these innovations. However, they need clarity in terms of coordination and standards in order to define their own product roadmaps and allocate resources and capital to their implementation.

The public sector will have to engage with the private sector to proactively deliver the clarity that mobilizes private sector innovation. This can include (but is not limited to) the following:

- Defining National Airspace System capability milestones in terms of requirements sets.
- Defining agreed-upon detailed requirements that support technical implementations of systems in the National Airspace System and that support increasing capability and complexity of operations. These may

include requirements describing automation levels, system structure, system component responsibilities, and so on.
- Driving creation of standards, in collaboration with industry, based on system requirements to detail the system protocols, data exchange, communications, interoperability, and other areas.
- Identifying and managing long lead-time research to support future capabilities.

For the public sector to succeed in this new mission, it will need to realign itself in terms of its mandate, capabilities, and authority. This aspect is covered further in Chapter 5 of this report.

Making Progress

If the right framework is created to enable private sector innovation, it will be possible to move faster to break down the complexity of advanced aerial mobility systems and build U.S. competitiveness in the process. The experience gained in applying advanced aerial mobility at each capability milestone to missions for which it delivers value will constructively feed into insights that inform development of the next level of capability. This follows historic precedent of other complex systems society has adopted and fulfills on the guiding principles of the vision.

PROMOTING U.S. COMPETITIVENESS

The committee heard from a broad cross section of industry experts across a wide variety of fields, disciplines, and areas of expertise. Over the course of this study, it has become clear that the advanced aerial mobility market is poised for massive and rapid evolution and growth over the coming decade and that many other countries are viewing the advanced aerial mobility opportunity space as a potentially transformative societal element and emergent driving force of their economy. Mastery of advanced aerial mobility, given its wide-ranging impacts on society and the economy, will be one of the highlights of civilization. The size and importance of this vision means that governments are viewing it as strategic and taking various approaches to compete for leadership and prepare for its adoption. U.S. leadership in advanced aerial mobility is in no way assured, despite the nation's strong legacy in aerospace. The new technologies enabling advanced aerial mobility are widespread across developed and developing countries. Their fundamental nature lowers the barrier to entry, despite the complex systems engineering involved. The subject of competitiveness is further explored in Chapter 3.

ULTIMATE CAPABILITIES OF THE VISION

In sum, the national vision for advanced aerial mobility is an airspace system that can support high-scale flight operations supporting any number of applications, using vehicles small and large, carrying passengers or cargo, and operating over cities or in remote areas. This system will maintain the highest levels of safety yet be designed to be inherently flexible, supporting a diverse array of flight operations for any number of customized applications. It will be environmentally responsible, including minimizing noise effects, and be accepted by society and embraced as a new transportation mode. It will support the particular needs and characteristics of electrically propelled flight and eVTOL-capable flight. It will support both manned and unmanned aircraft as well as aircraft of all sizes. It will support a very large number of ground destinations and fluid flight operations between them. It will support all-weather operations tailored to the needs of this type of transportation system.

Fully realizing this vision may take many years. However, there are high-impact victories to be had at milestones along the way that will create valuable new markets, grow industries, and positively impact society. Progress will be achieved through a succession of increasingly complex and high-scale flight operations types, with each building upon the standards, technologies, and experience gained from those that preceded it. This succession will not be spontaneously self-assembled but rather will have to be designed and agreed upon by all stakeholders such that they build constructively upon each other and such that the private sector is given the clarity from regulators and national and international standards development organizations needed for them to deploy resources and capital toward these goals.

3

Market Evolution

Given the key barriers to advancement, the evolution path and timeline for advanced aerial mobility applications remains ambiguous. There are many perspectives regarding the scope and size of the potential market space from which a few common themes have been extracted and correlated. The committee was presented with a wide range of various projected times in the future for advanced aerial mobility operational implementations of different types, each a snapshot of an isolated scenario. For example, initial urban air mobility (UAM) operations in 2022/2023, to 2028 to 2030 for viable markets for air metro and "last-mile" delivery operations, respectively.[1] Advanced aerial mobility operations like those of a taxi service were not envisioned in the National Aeronautics and Space Administration (NASA)-sponsored UAM market studies as having a viable market in the 2030 time frame.[2] However, these projections have significant sensitivity to their underlying assumptions and should not be taken at face value but rather considered as a tool for deeper thought about the steps required to achieve them. Rather than debate the timing, it is more informative to look inside the process and journey to get the milestone. From this we can more clearly articulate the challenges and thereby work to better affect the outcome.

While the committee has not developed predictions about the pace of advanced aerial mobility market evolution, it is likely that the market will develop in step with new capabilities that are incrementally introduced, such as when necessary vehicles, infrastructure, and operational procedures are developed, tested, and certified by airworthiness authorities. The Federal Aviation Administration (FAA) has endorsed the use of a "safety continuum," in which the level of airworthiness certification is varied as a function of the risk of operations in which a manned or an unmanned aircraft will engage. Given that the FAA puts its highest priority on aviation safety, advanced aerial mobility operational implementation will most likely be evolutionary, slow and methodical, with regard to an increased operational risk profile, not revolutionary.

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[1] As characterized in marketing studies presented to the committee, air metro operations have predetermined routes and schedules, much like a bus network. "Last mile" is the final delivery of a product or service to the consumer. Delivering mail or a package to a door step dispatched from a nearby distribution site or even a delivery vehicle is the most common vision. "Middle mile" is movement of cargo or people to or from a terminal location to an intermediate location for further transport. Carrying a FedEx package from Memphis International airport to a distribution center for further delivery action is a good example.

[2] Booz Allen Hamilton, 2018, *Final Report: Urban Air Mobility (UAM) Market Study*, submitted to NASA on November 21, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190001472.pdf; McKinsey & Company, 2019, *Urban Air Mobility (UAM) Market Study*, submitted to NASA in November.

For example, air metro operations may well have their initial operational implementation with a pilot in the vehicle, working within existing regulations with regard to, for instance, "see and avoid" requirements and using the generally less sophisticated advanced aerial mobility traffic management infrastructure available in the early days. The committee was provided input from several participants in the advanced aerial mobility industry that are consistent with such an approach. As sufficient confidence is earned in air metro operations (via current operators such as UberCopter, VOOM, Blade, and others), as well as in their certified vehicles and the supporting infrastructure through operational implementation and experience, the stage will be set for greater autonomy of advanced aerial mobility vehicle operation.

In order to accelerate the eventual operational implementation of advanced aerial mobility, related research, development, and experimentation activities should have this type of market evolution in mind and seek to reduce uncertainties where they exist. Four particular opportunities are described below for this purpose.

BUILDING TOWARD AN INTEGRATED AIR TRAFFIC MANAGEMENT SYSTEM

As noted previously, a key infrastructure requirement for operational implementation of advanced aerial mobility is one or more systems that supply effective air traffic management (ATM) for operations not presently covered by voice-centric FAA ATM services.

The committee was provided updated information on NASA's multiyear Unmanned Aircraft System Traffic Management (UTM) program. The UTM program has demonstrated four increasingly challenging technical capability levels for unmanned aircraft system (UAS) operations in low altitude airspace, most recently (in the summer of 2019) complex beyond visual line-of-sight operations in an urban environment for both nominal and contingency situations.

NASA is now looking at expansion of the UTM system concepts to advanced aerial mobility as a whole, including for emerging electric aircraft that could be "dually capable" to interact within the low-altitude UTM environment using the UTM construct as well as inside the current ATM environment with traditional (heretofore almost exclusively manned aviation) FAA air traffic control (ATC). Initially, support of such expanded operations might be achieved through effective interfaces between UTM and the ATM system. Long term, an integrated National Airspace System will be most efficient when capable of supporting aircraft operations of all types without the need for segregation to separate airspace for manned and unmanned traffic.

Alongside system architectural integration of UTM with the ATM system, the policy barrier of how UTM is to be financed has been a question that the FAA's Drone Advisory Committee is addressing. As a roadmap to an integrated air traffic system is laid out, this issue remains relevant.

Finding: NASA has developed a promising concept for UTM, but is still in the process of extending this concept to include general advanced aerial mobility operations and integration with existing air traffic. Routine advanced aerial mobility operations above 400 feet in all classes of controlled airspace will require key infrastructure for operations not presently covered by voice-centric FAA ATM services. The committee is encouraged by early coordination with the FAA and industry on UTM.

Recommendation: NASA, in coordination with the FAA, should perform research to extend Unmanned Aircraft System Traffic Management concepts to accommodate emerging advanced aerial mobility traffic in all classes of airspace.

A FOCUSED EXPERIMENT IN CARGO TO IDENTIFY GAPS AND OPPORTUNITIES IN THIS MARKET SEGMENT

While the maturation and evolution of this overall market will take time, patience, skill, and investment in order to bring it to fruition, many of the stakeholders and early adopters appear ready now. They will not wait the decade or more that historically it could take the public sector for things to start moving. One potential solution might be to focus solely on a portion of the market that is more mature and potentially viable in the near term.

The cargo transport market for remote areas or over water may represent such an opportunity for advanced aerial mobility, providing realistic operations in lower-risk geographical areas. It frames many of the key seminal challenges that face this emerging market in a manner that makes them tractable and surmountable for test/implementation in a real-world environment—for example, reduced population density and minimal air traffic density. This forms the basis of a risk-based approach that begins with vehicle operations in remote areas or over water, later incorporating vehicles with people on board. Operations are then tested in more populated areas and last evolve to support passenger operations over urban areas.

The committee was briefed by several representatives of U.S. package delivery services, all with enthusiastic discussions of current investments and flight demonstrations. These are commercially driven entities that stand to profit from the increased delivery capability and reduced personnel costs of the envisioned systems. These briefings included discussion of the initial small aircraft, rural operations as experiments in vertical, autonomous operations that allowed development in more benign environments. But all of the representatives indicated that their plans included entry into suburban and urban environments as soon as FAA approval was granted.[3]

The committee found that the commercial entities already had significant sophistication as to cargo size needs and market forces that they had to respond to. The committee concluded that these commercial operators and investors were far more capable of defining the market size for each class of vehicle and that the fundamental issues to be defined and solved were universal to virtually all autonomous vertical vehicles.

Large Cargo Advanced Aerial Mobility operations. Current business plans for at least one original equipment manufacturer include developing a universal vehicle agnostic autonomous control and servo package that can retrofit into existing airframes, created partly by the Defense Advanced Research Projects Agency Aircrew Labor In-Cockpit Automation System program and currently in a convincing flight demonstration program. “Platform agnostic design supports multiple vehicles enabling mission tailoring,” according to one press release, so that there is strong market participation in creating autonomous air vehicles that, by dint of their current piloted participation in large cargo operations, will easily answer questions of the infrastructure for loading/unloading, and meshing of these autonomous operations with manned operations.[4] While initial operations do not seem to be planned as electrically powered vertical takeoff and landing, these large autonomous vehicles will need to be part of the autonomous vehicle overall integration into the National Airspace System that is part and parcel of this report’s scope.

Small Cargo Advanced Aerial Mobility operations. The committee was briefed by the United Parcel Service (UPS) and shown video of current “drone” package delivery systems integrated into the classic UPS brown delivery trucks.[5] It is clear that the market will define the payload capacity, range, and speed of small drones. As far as delivery methods in the “last mile,” (i.e., to the customer, which could be a household or business) the committee saw several examples. The commercial delivery experts who are developing the vehicles are certainly aware of the issues, and several innovative methods of home delivery in suburban environments are currently being flown.

In addition, this initial implementation could benefit from an inherent acceptance of baseline business cases owing to these clear advantages of demonstrating deployment on a realistic scale in communities that stand to derive credible value proposition. This idea has been developed, matured, and endorsed by key stakeholders such as UPS, Federal Express, and Amazon.[6] These operators have initially explored these markets and unmanned cargo operations in detail, establishing a baseline perspective that these markets can be viably sustained. This greatly increases the committee’s confidence that these specific implementation areas are viable and promising first adopters of large-scale advanced aerial mobility deployment and associated technologies that enable the cargo delivery market.

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[3] A recent example of testing involves Federal Express; see FedEx, 2019, “Wing Drone Deliveries Take Flight in First-of-its-Kind Trial with FedEx,” October 18, https://about.van.fedex.com/newsroom/wing-drone-deliveries-take-flight-in-first-of-its-kind-trial-with-fedex/.

[4] Ibid.

[5] UPS, 2019, “UPS Flight Forward Attains FAA’s First Full Approval for Drone Airline,” October 1, https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1569933965476-404.

[6] UPS has an approved but limited Part 135 approval to deliver medical supplies at the WakeMed facilities in North Carolina. The Federal Aviation Administration grants the authority to operate on-demand, unscheduled air service in the form of a Part 135 certificate. Air carriers authorized to operate with a 135 certificate vary from small single aircraft operators to large operators that often provide a network to move cargo to larger Part 121 air carriers. Many Part 135 operators offer critical passenger and cargo service to remote areas.

BOX 3.1

United Parcel Service (UPS) has been granted by the FAA Part 135 certification to operate commercial drone flights in the trademarked UPS network under a subsidiary business called UPS Flight Forward, Inc.

The new subsidiary is a recently incorporated business that could receive Part 135 certification as early as this year, putting UPS on track to have one of the first fully certified, revenue-generating drone operations in the United States. When approved, this certification lays the foundation for drone flights beyond an operator's visual line of sight and for flights occurring day or night. Such flights are highly restricted in the United States and approved only by exception.

"UPS is committed to using technology to transform the way we do business," said Scott Price, UPS chief transformation and strategy officer. "UPS's formation of a drone delivery company and application to begin regular operations under this level of certification is historic for UPS and for the drone and logistics industries."

In contrast to more-limited FAA certifications for drone flights by other companies, UPS Flight Forward would operate under the FAA's standard Part 135 certification. This legal certification confers a legal designation to a company: certified Air Carrier and Operator.

Currently, UPS operates drone healthcare deliveries in a specific use case under FAA Part 107 rules. In March, UPS initiated the first FAA-sanctioned use of a drone for routine revenue flights involving the transport of a product. The FAA approval was for a contractual delivery agreement in the United States at WakeMed's flagship hospital and a campus in Raleigh, North Carolina. In this program, the company delivers medical samples via unmanned drones, supplementing a ground courier service. UPS intends to expand its drone delivery service to other hospitals or campus settings.

SOURCE: Excerpt from recent UPS press releases from UASMagazine.com, UPS, 2019, "With UPS Flight Forward, Drone Delivery Operations Near Reality," July 29, http://uasmagazine.com/articles/2050/with-ups-flight-forward-drone-delivery-operations-near-reality.

Focusing on a rural cargo delivery system could provide a number of benefits in the establishment of a broader advanced aerial mobility market. First, there is a compelling need to cover significant distances and circuitous routes with a reduced number of cargo assets. Second, several major air carriers have explored the viability of utilizing advanced aerial mobility vehicles for rural cargo delivery already. Some have even demonstrated how small drones and conventional delivery trucks can work in concert in order to achieve superior overall efficiency system-wide, reducing time and cost in delivering goods to rural customers (see Box 3.1).

Although the example above involving a pilot project in Raleigh, North Carolina demonstrates that test projects in urban areas are possible, they still present more hurdles than rural areas. The operation of rural cargo delivery service could allow operators to explore the societal acceptance levels of operating such vehicles on a regular recurring tempo and with increasing frequency. On a much larger and more impactful scale, these drones will face the same challenges but in a dense urban environment.

Last, rural areas offer the reduced population, vehicle density, and air traffic density that should lend themselves well to refining complex operations, allowing prototype UAS cargo logistics services to "work out the kinks" in cargo operations. This simultaneously provides a great benefit to the local community and allows a true advanced aerial mobility operation to be tested and vetted for future use.

Finding: A risk-approach to operations rollout can include a progression starting with cargo in rural areas and moving to people in urban areas. The rural cargo market appears to be a good match for early autonomous drone operations due to reduced population and spectrum density, minimal air traffic volume, reduced ground clutter and ground obstacles, reduced operational risk, and the need to often cover long distances between points with minimal logistics footprint.

Finding: The commercial cargo market is ready to adopt an operationalized advanced aerial mobility capability as a cost-saving measure in order to derive greater efficiencies within its business space, particularly focused on deployment in rural markets and as a hybrid capability with its ground cargo distribution infrastructure.

Finding: The commercial cargo industry is potentially willing to fund/invest in technology development as required to do so. These operators have already conducted economic analysis that highlights potential break-even points within the next 1-2 years.

Finding: The economics and compelling value propositions to support the deployment of a cargo carrier UAS exists and has been quantified by commercial cargo operators.

Finding: The commercial cargo market appears to be a receptive, prepared, and very promising "initial adopter" of autonomous cargo drone technology/capability for rural domestic cargo operations. This posture is fueled by the need to enhance delivery throughput, increase cargo velocities, and define future competitive discriminators.

Recommendation: NASA should, within the next year, establish strategic partnerships with first adopter cargo logistics providers and relevant manufacturers. The partners should focus on maturation of technologies aimed at deploying autonomous cargo drone delivery of small, medium, and large size within 3 years.

RESEARCHING OPERATIONAL CONCEPTS OF INCREASING COMPLEXITY TO DISCOVER EMERGENT EFFECTS AND REDUCE UNCERTAINTY ON STANDARDS FOR OPERATIONS

Having heard from many technology providers, service providers, regulatory agencies, academicians, and original equipment manufacturers seeking to enable the emergence of a UAM marketplace, the committee is well-positioned to combine these pieces and assess the overall robustness and viability of the marketplace as a whole. In considering the various facets of this enormously complex technical, regulatory, and societal transformation, there is a disparity between stakeholders who have framed their perspective upon past lessons learned, proven standards of safety, and regulatory discipline, and ambitious "first movers" who are taking a principled (i.e., responsible and not reckless) yet far more aggressive approach to prove the viability of this emerging market.

This dichotomy is both empowering and concerning. The intersection between these two disparate perspectives is at the heart of the advanced aerial mobility marketplace emergence and revolves around approaches to managing risk in the pursuit of safety and system capability. Perspectives differ on where system-wide risks are expected, how experience mitigating risks applies, and how new technologies change sources of risk or instigate known and qualified risks. While there is broad agreement on safety objectives, the approaches to the underlying factors and components differ markedly, primarily driven by differences in past experience and familiarity with the various best practices, design and operating methodologies, and new technologies involved. Ultimately, the constructive intersection of these perspectives may define this sector's ability to evolve to its full potential. There are many viable and impressive technology/platform providers but because they are new to the heavily regulated aviation industry, many of them do not have experience working with the authorities that will ultimately determine the fate of their autonomous mobility product offering.

Further, when considering matters from a global lens, the committee is concerned that the U.S.-based aviation industry may actually be at a distinct competitive disadvantage precisely because the domestic U.S. commercial aviation industry is itself so mature and well developed. Given its maturity, long track record of safety, and the high standards of regulatory management, the country may actually be at a disadvantage as this market emerges. One reason for this potential disadvantage is the possibility that early adopters across the globe may not feel as encumbered or obligated to operate these platforms and systems with the same rigor and discipline as will be likely required and mandated for operation in the United States. Much is still unknown about large-scale operations, the robustness of the technological solutions being fielded, and ultimately the level of safety that can be achieved. As the industry gathers these data, it is imperative that sharing and collaboration take place on a global basis in order to ensure that all adopting regions have the benefit of the learning that is going on in any one portion of the market.

Finding: There is real risk that the United States may not act quickly enough from a regulatory standpoint to achieve the full potential of advanced aerial mobility. This may result in the nation essentially ceding a leadership role in the definition of the enhanced aerial mobility market segment in the near term if things are done as they have always been done or if this new air mobility paradigm is forced to fit within the current airspace system regulatory framework.

Beyond new air vehicles, advanced aerial mobility requires a vastly more capable flight environment. As discussed in Chapter 2, gaps exist between today's National Airspace System and what the community will build. The task touches systems tying together air vehicles, airspace, surveillance, communications, and infrastructure. One question is where to begin and how to coordinate the process, given innumerable system interdependencies and needs of different stakeholders. Further, there is a question of how each participant gains the clarity needed to commit resources to build and contribute their part.

Clarity comes from an agreed goal and understanding of the big picture. The plan must be collaborative, involving public and private stakeholders. Beginning at system-wide scope, the community should create a high-level roadmap describing a progression of milestones, each a new capability for the airspace system (see Figure 3.1).

Systems in other industries have enjoyed a more passive evolution, converging on design by letting innovations compete, with the best rising to the top. However, the realities of the National Airspace System—with its low risk tolerance, public and private stakeholders, and strong regulatory involvement—make it unworkable to self-assemble new capability out of a mass of independent innovation efforts.

A capability roadmap guides to the standards that are needed. Standards are important for bridging from high-level requirements to detailed implementation. Through ongoing work, standards development organizations like ASTM, RTCA, SAE, ANSI (American National Standards Institute), and others are developing system and operational performance requirements leading to operational approvals and certification of UAS. Existing standards development processes include the creation of foundational concepts of operation and scenarios that describe an integrated airspace model supporting advanced air mobility.

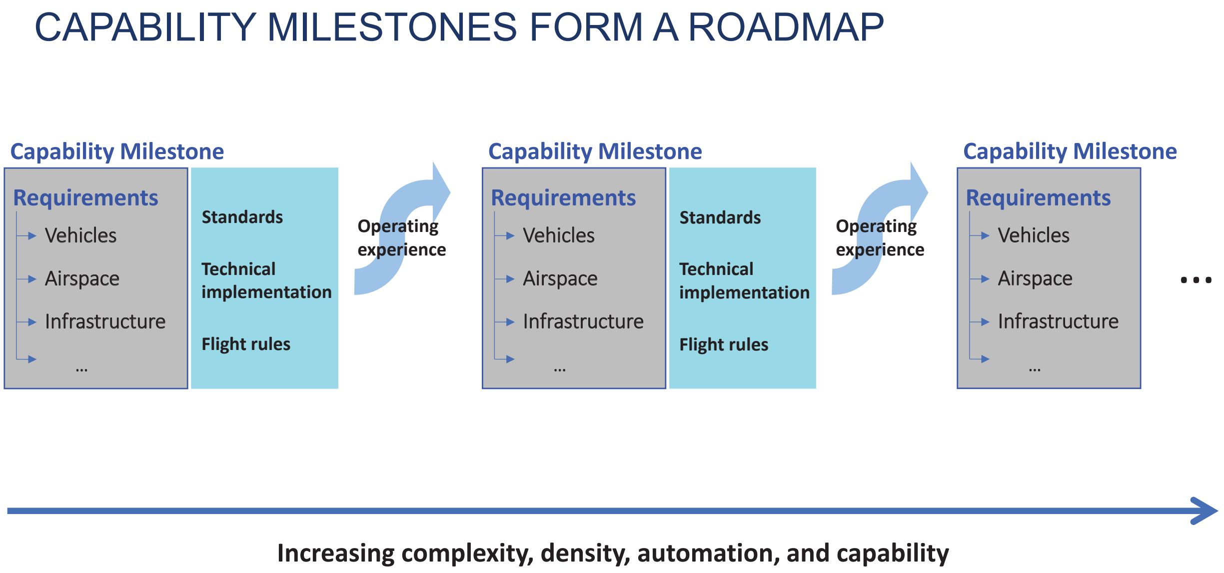

FIGURE 3.1 A capability roadmap lays out a progression of high-level requirements for the National Airspace System as a series of milestones, delivering increased complexity and density of operations at each step.

While standards define specifics, they depend on the external context of a bigger picture for their requirements and constraints. A well-defined, high-level architecture that describes the system of systems, subsidiary roles and responsibilities, and the points of interface is critical to identifying where standards are needed and what they need to achieve.

It follows that the starting point is to collaborate on the capability roadmap. As a clarifying example, instrument flight is a capability the community has already built. Autonomous flight, in various forms, could be a future capability. The roadmap drives agreement on the vision and setting of priorities; it helps to identify gaps, while providing the clarity to enable commitment of resources to execution. However, balanced against clarity should be flexibility, in particular with respect to how the capability might be applied to new operations or business models.

Building new capabilities into the airspace system will be a stepwise journey. The historical progression of capability supporting instrument flight reflects this. Each future advance, whether for drones or piloted flight, can be thought of as a capability milestone. Milestones can break the larger problem down, reducing complexity, while the experience gained at each step can inform the definition and development of the next.

Getting the milestones right is critical. The selection of a milestone (i.e., the capability it delivers) is as important as clarity in requirements and the collaborative process by which they are derived. How feasible is the milestone? How useful will the milestone be in enabling new operations in the airspace? These considerations should be balanced. Each milestone must define critical requirements including roles and responsibilities, high-level architecture, and required performance levels.

The process to define a milestone should take input from all key stakeholders, including regulators, other affected parts of the public sector, and the private sector. The process should be conducted by those with authority to make decisions for the National Airspace System, and they should be held accountable for timely delivery of the milestone and its full set of requirements. A coordinated, purposeful approach to requirements and the roadmap can identify needs for standards earlier, yielding a better end result and saving years of time.

A goal should be to achieve consensus through a collaborative process that is held accountable for its progress, in order to move fastest. A goal should be to supply the private sector with the clarity needed to commit resources. With clarity, the private sector has proven able to define product and strategy and to deliver rapid innovation through commitment of financial and human capital.

A goal should also be to provide regulators with a structured performance-based safety case to enable them to commit to milestones and requirements early, thus driving further clarity for all other stakeholders. This buy-in early in the process is crucial.

Finally, milestones and their respective requirements should be very clear in support of the above goals but remain flexible to technical implementations, striking a balance between the need for an organized plan and the need to iterate and be flexible to entrepreneurial approaches that produce unexpected leaps forward. Through a performance-based approach to requirements, this can be achieved while also providing a clear pathway to integrating future improved capabilities.

In summary, the challenge becomes more manageable when the community first agrees on a roadmap of high-level requirements. Requirements can design-in safety by construction and build a performance-based safety case that regulators can get behind from the beginning. Clarity from the plan gains buy-in from the private sector, unlocking investment and creating a host of opportunities. The right plan is the biggest success factor to integrating autonomous flight into the airspace system in a timely manner.

Through ongoing work, standards development organizations like ASTM, RTCA, SAE, ANSI, and others are developing system and operational performance requirements leading to operational approvals and certification of UAS. The existing standards development process includes the creation of foundational concepts of operation and scenarios that describe an integrated airspace model supporting advanced aerial mobility.

Finding: Advanced aerial mobility will commercialize only based on clarity from regulators and the perceived risk of timely regulatory progress, which will be required to support given new flight operation types or applications. This is particularly true where operation types or applications depend on regulatory approval of new technology, increased automation, or other changes to the National Airspace System necessary to support the required scale or sophistication.

FIGURE 3.2 A staged rescue operation using a multicopter to deliver medical response personnel to the scene of an accident. Countries like Germany are actively testing response times for emergency response advanced aerial mobility vehicles. SOURCE: Volocopter ADAC staged rescue operation, ADAC Foundation, Volocopter, © 2019.

Finding: Urban air taxi service for the general public, due to its requirements for vehicle performance, safety, sophisticated operations, infrastructure, operating costs, and system scale and tempo, is one of the most demanding applications of advanced aerial mobility. However, it is an attractive application once the system capabilities are in place.

Finding: Numerous other applications that are less demanding can serve as opportunities to build experience and refine technology on the way to establishing the full set of capabilities required for urban air taxi services. These applications can also play an important role in establishing societal acceptance of the technology.

Finding: Near-term applications can include cargo delivery and surveillance operations in less densely populated areas. Applications can include emergency medical services (see Figure 3.2), first responders, disaster relief, corporate transport, cargo logistics, inspection of electric power facilities (e.g., transmission lines) in remote areas, and others. Given the new capabilities technology delivers to flight, the applications of advanced aerial mobility are wide-reaching and difficult to foresee.

Finding: A National Airspace System that delivers safety, access for increasingly autonomous systems, and scalability, yet that makes few constraining assumptions about specific anticipated flight operations, will deliver flexibility to explore applications of advanced aerial mobility and to adapt gracefully to future increases in scale and capability.

Finding: A definition of a series of successively more complex capability milestones and associated requirements sets including the architectural components of the system that will support them is needed. These requirements sets embody progressively more sophisticated operations in the National Airspace System that deliver increased capabilities and scale to the system and may touch vehicles, airspace, and infrastructure (see Figure 3.3). These requirements sets serve as a target for standards development and the systems based on them and ultimately

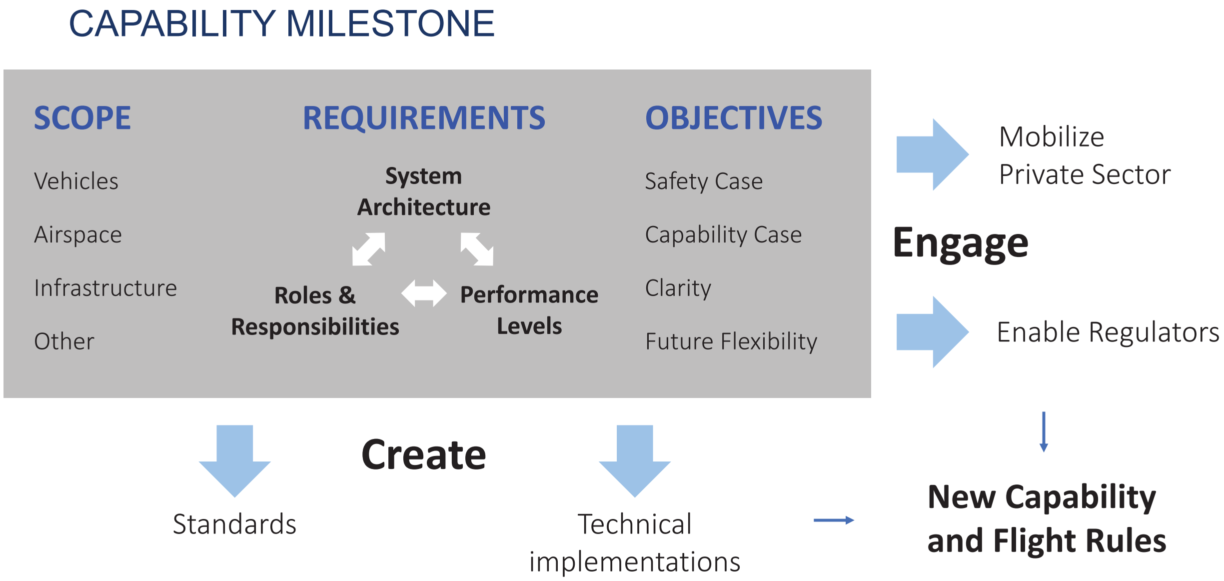

FIGURE 3.3 Requirements sets will need to be defined in order to enable more sophisticated operations, like those of advanced aerial mobility vehicles and platforms, in the National Airspace System.

new flight rules sets for the National Airspace System. Architectural decisions include specifications sufficient for future standards and implementation development in areas such as the following:

- System architecture framework—defining the principal elements, functions, and interfaces of the system;
- Roles and responsibilities throughout the system;
- Communications—assumed communications capabilities including decisions for spectrum, data exchange, and cybersecurity standards;
- Approaches to adapting architectural function and components over time; and
- Evolution of existing safety evaluation approaches.

Recommendation: NASA should prioritize research that develops architectures, requirements, and supporting technologies to enable integrating advanced aerial mobility into a future National Airspace System.

ENHANCING AND REFINING THE NASA NATIONAL CAMPAIGN PROGRAM

NASA's desire to develop a robust portfolio of technologies that enable mission agencies and commercial firms to create safe and effective advanced aerial mobility is challenged by significant market uncertainty, including uncertainty sourced from the emergence of nontraditional participants and their novel approaches, objective functions, and constraints derived from unique business models. By definition, highly entrepreneurial approaches are distinguished by their disruptive approach to perform some key function in advanced aerial mobility.

Therefore, it is important for NASA to document categories of disruptive effects and their interactions among effects to create a foundation for *learning* about, and then *accommodating*, these effects in NASA's investment portfolio. NASA's recognition of this appears to be a driver for creating the UAM National Campaign program.[7]

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[7] NASA changed the name of the program from Grand Challenge to National Campaign soon after this report was first released. The new name has been used in the final version of this report.

The stated goal of NASA's UAM National Campaign program is to improve advanced aerial mobility safety and accelerate scalability through integrated demonstrations of candidate operational concepts and scenarios. This goal is supported by the following overarching objectives:

- Accelerate Certification and Approval
- Develop Flight Procedure Guidelines
- Evaluate the Communications, Navigation, and Surveillance Trade-Space
- Demonstrate an Airspace Operations Management Architecture
- Characterize Vehicle Noise

Flight experiments under the National Campaign are coordinated in design and execution with the FAA and industry participants. In particular, the experiments are structured around scenarios with specific outcomes that support the five overarching objectives. These scenarios are as follows:

- Scenario 1—Trajectory Planning and Compliance
- Scenario 2—Aircraft and Airspace Operations Management Data Exchange and Coordination
- Scenario 3—UAM Port Operations
- Scenario 4—Noise Evaluation and Response
- Scenario 5—Communication, Navigation, and Surveillance Contingencies
- Scenario 6—Air-to-Air Conflict Management
- Scenario 7—Constrained Conflict Management

The potentially large number of new entrants is perhaps most striking in the variety of firms offering aircraft concepts that target the advanced aerial mobility market. Many of these have never applied for certification for commercial (i.e., passenger or cargo) transportation; thus, they will find it challenging to deal with the FAA, and the FAA will also find it difficult to deal with these inexperienced companies. The NASA National Campaign program will be successful if it continues to evolve to accommodate these new entrants. This is especially important because new entrants can introduce new safety risks.

Finding: NASA's continual refinement of the National Campaign program and scenarios based on feedback of industry as central players in the National Campaign experimentation is commendable (and essential) given the many opportunities (but unknowns) related to new entrants and entrepreneurial approaches.

Finding: One of NASA's priorities for the National Campaign program is to pioneer the research, systems, and concepts of operations to enable advanced aerial mobility in the National Airspace System. This is a critical enabler with benefits for all, as it will assist in driving clarity from regulators with respect to system architecture, operations, and regulatory requirements. However, the structure and schedule of the National Campaign program to drive these goals means that many companies are either unable or unwilling to participate.

Finding: An additional outgrowth of NASA's work in the National Campaign program is the generation of data, best practices, resources focused on advanced aerial mobility, and other findings that are valuable to all U.S. participants in the industry. If captured and disseminated effectively, these assets can accelerate progress across the industry and promote continued U.S. leadership in aerospace.

Recommendation: In partnership with industry, NASA should continue building on and enhancing the National Campaign program and develop its learning outcomes into formalized best practices, tools, resources, and training programs available to all U.S. stakeholders.

The next chapter addresses some of the most difficult issues that will face participants in advanced aerial mobility systems, notably how to achieve safety, security, and contingency management within the cyber environment.

4

Safety, Security, and Contingency Management

Three of the requirements needed for acceptability that would allow advanced aerial mobility to grow beyond the small scale that exists today are safety, cybersecurity, and how they relate to autonomy. While autonomy is not critical for achieving some types of urban air mobility (UAM)/advanced aerial mobility, some levels of autonomy will be required when human control is not adequate to assure safety in high-speed, crowded environments. Autonomy will be necessary to overcome the human factor problems that result from operating complex, high-speed equipment in a crowded environment. Furthermore, high levels of automation will most likely be required to achieve the economic benefits. To provide autonomy, challenges in assuring the safety and security of highly automated and thus software-intensive systems will have to be overcome.

SYSTEM SAFETY

Accidents and the perceived lack of safety in enhanced aerial mobility will be a major challenge, potentially preventing the acceptance of this technology. The hardware safety issues are easily handled as the hardware in this environment will bear many similarities to that used today in certificated systems, perhaps with upgrades in acoustics and electrical systems. Measures to manage safety in drone systems are in place today and are maturing. However, there are major challenges in ensuring acceptable safety and cybersecurity for manned vehicles.

System safety is not only with respect to the vehicles themselves. It includes the safety of the vehicles in the environments in which they will be used, including such things as collision avoidance, contingency management (e.g., to handle Global Positioning System or traffic management outages), and traffic management. Inability to meet these challenges will result not only in negative public perceptions of safety and unwillingness to participate but also in liability, insurance, legal, and other social challenges that could prevent a UAM system from achieving traffic levels above those in existence today.

The committee heard about two approaches to ensuring safety while using autonomy: testing and simulation. Unfortunately, neither of these are sufficient for complex, software-intensive systems. The usual safety engineering approaches will need to be utilized and scaled to handle software and the types of systems envisioned.

Testing

Exhaustive testing of software is impossible. The problem can be explained by examining what "exhaustive" might mean in the domain of software testing, as follows:

- *Inputs*. The domain of possible inputs to a software system includes both valid and invalid inputs, potential time validity of inputs (i.e., an input may be valid at a certain time but not at other times), and all the possible sequences of inputs when the design includes history (which is almost all software). This domain is too large to cover any but a very small fraction of the possible inputs in a realistic time frame.
- *System states*. Like the number of potential inputs, the number of states in these systems is enormous. For example, TCAS, an aircraft collision avoidance system, was estimated to have 10^{40} possible states, and even today, after many years in service, problems are still being found and fixed.[1] Note that collision avoidance is only one small part of the automation that will be required to implement autonomous (and even nonautonomous) vehicles.
- *Coverage of the software design*. Taking a simple measure of coverage like "all the paths through the software have been executed at least once during testing" involves enormous and impractical amounts of testing time and does not guarantee correctness, let alone safety.
- *Execution environments*. In addition to the problems listed so far, the execution environment becomes significant when the software outputs are related to real-world states that may change frequently, such as weather, temperature, altitude, pressure, and so on.

In addition, even if it were possible to test the software exhaustively, virtually all accidents involving software stem from unsafe requirements.[2,3] Testing can show only the consistency of the software with the requirements, not whether the requirements are flawed. While testing is important for any system, including software, it cannot be used as a measure or validation of acceptable safety.

Simulation

All simulation depends on assumptions about the environment in which the system will execute. Autonomous cars have now been subjected to billions of cases in simulators and have still been involved in accidents as soon as they are used on real roads. The problems described for testing apply, but the larger problem is that accidents occur when the assumptions used in the simulation do not hold. Another way of saying this is that some accidents occur because of "unknown unknowns" in engineering design. There is no way to determine what the unknown unknowns are; thus, simulation can show only that the industry has handled the things it thought of, not the ones it did not think about.

A WAY FORWARD

The problem is not hopeless. System safety engineering has never depended exclusively on testing or simulation, so it is surprising that these two approaches are being suggested for advanced aerial mobility and other complex system development today. To handle all the states, even when an enormous number is involved, system safety engineers use modeling and analysis. An abstraction or model of the system is created, and that model is analyzed to ensure that the system it represents cannot get into a hazardous state.

Safety modeling and analysis tools have been used for the past 60-70 years in safety-critical systems. There are some technical limitations, however, that need to be overcome in these traditional techniques as they were developed before computers were used in hazardous systems. They do not work for today's level of technical complexity although people still try to use them, perhaps due to the lack of alternatives.

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[1] N.G. Leveson, M.P.E. Heimdahl, H. Hildreth, and J.D. Reese, 1994, Requirements specification for process-control systems, *IEEE Transactions on Software Engineering* SE-20(9).

[2] N. Leveson, 1995, *Safeware: System Safety and Computers*, Addison-Wesley, Boston, Mass.

[3] R. Lutz, 1993, Analyzing software requirements errors in safety-critical, embedded systems, *Proceedings of the International Conference on Software Requirements*, https://doi.org/10.1109/ISRE.1993.324825.

There are currently military operators and contractors that have accumulated significant amounts of experience with unmanned aerial systems, including alongside piloted aircraft. However, these aircraft often operate in restricted or highly controlled airspace (e.g., military ranges within the United States or over conflicted territory overseas) and not over civilian areas. Military drones have an accident rate that would be totally unacceptable in civilian aviation or where human life is involved. The military has acknowledged the loss of hundreds of drones in the past 10 years out of a relatively small number of total flights compared to civilian aircraft. The numbers of accidents per thousand flight hours are a better measure than absolute numbers of crashes and demonstrate that substantial improvements in reliability will be required for commercial drone operations.[4]

The first limitation of traditional hazard analysis tools is that they handle hardware but not software. Attempts to use the same models and analysis methods for software do not work because of the unique nature of software compared to hardware. Hardware fails in a probabilistic fashion. Software does not fail probabilistically. In addition, traditional safety analysis is based on a model of accident causality that assumes that accidents are caused by the failures of system components. This assumption is usually acceptable for purely hardware systems, but nobody is building systems today without software components.

Software does not fail like hardware. Instead, it almost always executes the instructions it was given.[5] An accident results only if the instructions are unsafe in the environment in which it is executing. It is not simply a matter of the software not satisfying its requirements. Those requirements may even change over time. Safety for hardware can be adequately estimated by the reliability of the hardware, but not for software.

The unique nature of software essentially reduces the software safety problem to the safety of the software requirements provided to the programmers. Showing the consistency of the requirements with their implementation in the software instructions can be handled using standard software engineering approaches. However, as noted, virtually all software-related accidents can be traced to unsafe requirements and related software requirements flaws. There needs to be a way of generating safe requirements or at least validating that the ones provided will result in a safe system.

One of the implications of the criticality of requirements is that safety must be built into the system from the beginning of development. Starting with a potentially unsafe set of requirements and relying on after-the-fact assurance will not be effective. Unsafe requirements are guaranteed to produce unsafe software. Changing the requirements late in development is impractical because of the astounding cost. The bottom line is that it is not possible to insert a property, like safety, into a system that does not already have it. Creating software that is safe from the beginning of development is a prerequisite for ensuring adequate risk in the final overall system and its components.

Because of the important distinctions between the systems for which traditional system safety engineering approaches were created and those being built today, which depend on software to a large degree, a paradigm change will be required in safety engineering. The nature of the paradigm change has been described,[6] and the first tools to deal with software-intensive systems have been created and are being used successfully to create safer systems. The greater efficacy of the new tools over the traditional techniques has been proven both theoretically and empirically, but extending these new modeling and analysis tools to handle the increasingly complex systems being considered, including UAM, will require research and either extensions to the tools available today or new tools.

Finding: Testing and simulation alone are not adequate to ensure safety in complex, software-intensive systems like UAM.

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[4] See, for example, *Wikipedia.com*, “List of UAV-Related Incidents,” https://en.wikipedia.org/wiki/List_of_UAV-related_incidents (for civilian accidents); J. Judson, 2018, “These Two Drones Are Leaders in Accident Rates. How Is the US Army Responding?,” *DefenseNews.com*, April 25, https://www.defensenews.com/digital-show-dailies/aaaa/2018/04/25/these-two-drones-are-leaders-in-accident-rates-how-is-the-us-army-responding/; A. Susini, 2015, “A Technocritical Review of Drones Crash Risk Probabilistic Consequences and its Societal Acceptance,” pp. 27-38 in *RIMMA Risk Information Management, Risk Models, and Applications*, Lecture Notes in Information Sciences, Vol. 7, https://www.researchgate.net/publication/291697791_A_Technocritical_Review_of_Drones_Crash_Risk_Probabilistic_Consequences_and_its_Societal_Acceptance; C. Cole, 2019, “Accidents Will Happen: A Dataset of Military Drone Crashes,” *Drone Wars*, September 6, https://dronewars.net/2019/06/09/accidents-will-happen-a-dataset-of-military-drone-crashes/.

[5] The exception occurs when the computer hardware, on which the software is executing, experiences a failure. This case is easily handled using redundancy and standard reliability techniques and is not considered further here.

[6] N. Leveson, 2012, *Engineering a Safer World*, MIT Press, Cambridge, Mass.

Finding: Traditional hazard analysis and safety engineering modeling and analysis tools do not apply to systems that include software for control. New types of tools will be required. Simply trying to extend existing tools to include analysis of software will not work.

Finding: The National Aeronautics and Space Administration (NASA), in coordination with the Federal Aviation Administration (FAA), could provide education on the need for new approaches beyond testing and simulation to the advanced aerial mobility development community.

Recommendation: In coordination with the FAA, NASA should support research on new, more powerful safety analysis tools that are widely used today that can be applied to software-intensive advanced systems.

CYBERSECURITY AND CERTIFICATION ASPECTS OF TECHNOLOGIES FOR ADVANCED AERIAL MOBILITY

Because of the dependence of advanced aerial mobility on software, cybersecurity will be a potential critical vulnerability. While cybersecurity efforts in the past have focused primarily on information security and privacy, the safety-critical element here changes the consequences and amplifies the challenge. For example, the cybersecurity challenge in advanced aerial mobility is not to prevent the theft of information from vehicles or passengers but to prevent outsiders from making the system and software behave unsafely.

Advanced aerial mobility faces several cybersecurity concerns: threats to onboard networks and code, attacks on vehicle/air traffic control (ATC) datalinks, and introduction of adversarial or incorrect data potentially used for safety-critical decisions and/or machine learning. Research in cybersecurity for onboard networks and traditional flight software is required to improve automated analysis and test to reduce software and data handling costs. Datalink security will require diversity and redundancy in communication links and new strategies for capturing cutting-edge cryptography strategies into living standards capable of assuring data authenticity despite evolving network attacks. Research is also needed to recognize and minimize the impacts of adversarial training examples in learning systems[7] capable of adapting to new or unexpected percepts or data sets.

It is almost impossible to keep hackers out of any systems today, and advanced aerial mobility systems will not be an exception. In terms of vulnerability, advanced aerial mobility will depend on the operation of other complex software-intensive systems such as ATC, Global Positioning System, and various types of shared communication systems. If advanced aerial mobility becomes an important infrastructure component in the United States, adversaries will find it a tempting target in any attack scenarios.

As with modeling and designing in safety, new approaches to cybersecurity are required to make advanced aerial mobility a success. The paradigm changes that have been proposed for ensuring safety are also applicable to cybersecurity, but again research and development is needed.

As with safety, traditional testing and simulation alone are not adequate to ensure cybersecurity in complex, software-intensive systems like advanced aerial mobility. A system that learns and adapts its behavior according to experience cannot be made secure by current techniques. New techniques are required, and NASA is a capable research agency that can support the FAA in developing them.

Finding: Current cybersecurity approaches that rely on threat analysis, maintaining impenetrable boundaries, and focusing primarily on information security will not be adequate for UAM missions involving learning and adaptive platforms.

Finding: Current airworthiness hardware and software cybersecurity techniques do not accommodate advanced aerial mobility platforms.

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[7] See X. Yuan, P. He, Q. Zhu, and X. Li, 2019, Adversarial examples: Attacks and defenses for deep learning, IEEE Transactions on Neural Networks and Learning Systems 30(9): 2805-2824.

Finding: NASA has initiated research into the area of complex autonomous systems to include leveraging of cybersecurity-related investigations performed by other agencies (April 2018 System-Wide Safety Project Plan, Section 2.1.4). The committee believes this is important research.

Recommendation: NASA should conduct research and development on cybersecurity for advanced aerial mobility systems.

Recommendation: Working with the FAA certification experts, NASA should develop potential software and hardware certification techniques and guidelines to verify and validate the performance of complex software and hardware, including nondeterministic functionality. This NASA research into methods to demonstrate performance will provide valuable input to the FAA, including material for advisory circulars, to help applicants in the certification process.

Notably, other government agencies, like the Defense Advanced Research Projects Agency, have also conducted work in complex autonomous systems, and significant work is being done in the private sector. NASA may learn from these other efforts and find potential partners in their efforts.

CONTINGENCY MANAGEMENT

Advanced aerial mobility is expected to require access for increasingly autonomous systems. Contingency response may be required when vehicle or infrastructure systems fail, environmental conditions are hazardous, passengers are distressed or disruptive, or special events require real-time rerouting. At the vehicle level, simplified vehicle operations or fully autonomous operations necessitate increasingly autonomous contingency management. At the traffic management level, increased traffic densities, route/mission complexities, and the need for new and novel contingency management necessitate autonomous traffic deconfliction and system-level contingency management.

Secure datalink is essential for advanced aerial mobility since voice-based communication has low bandwidth and introduces a multiple-second delay from event occurrence, to announcement on frequency, to comprehension by the human recipient. With secure datalink, real-time positions and velocities will enable software to rapidly identify and resolve conflicts in nominal and complex multivehicle route geometries that are impossible for human controllers to mentally model and manage. Air traffic contingency management will be required whenever unexpected bad weather is encountered, system elements fail or are attacked, or non-cooperative air traffic enters an airspace region normally occupied by cooperative traffic. Autonomous two-vehicle deconfliction and redundant datalinks are on the immediate horizon for manned aircraft and unmanned air systems. Weather and wind observations and forecasts improve each year. Autonomous multivehicle traffic deconfliction and increasingly resilient datalink systems are key technology needs for safe advanced aerial mobility in densely populated airspace.

A typical contingency management sequence requires initial detection or perception of a problem or an anomaly. An inference or a decision process triggered by the perceived problem leads to an action aimed at remediating or gracefully degrading in a manner that consistently maintains an acceptable level of risk. Perception systems have to detect situations in which contingency response might be required and have to balance missed detection versus false alarm risks. Traditionally, human pilot perception has been relied upon for contingency management based on feedback from aircraft automation and the environment. Advanced aerial mobility will require autonomous contingency management. *Autonomous systems* are distinct from traditional automation in their authority to make decisions and take necessary action without human oversight. Autonomous system authority is essential for advanced aerial mobility to assure risks are mitigated in time to restore a safe flight operational state despite the absence of a highly qualified onboard flight crew. Contingency management autonomy has to select and execute mitigation actions accurately and without vehicle-level loss of control, collision with other aircraft or obstacles/terrain, or unnecessary disruption to other air traffic or traffic management services. Contingency management autonomy will also need to integrate effectively with human system participants and evolve gracefully from legacy systems.

Finding: Due to the expected increase in number of aircraft operations per day and an observed steady-to-decreasing pilot training pipeline, autonomy for contingency management will be an essential component of advanced aerial mobility. Simplified vehicle operations with lower cost and reduced pilot training requirements are expected to be a precursor to fully autonomous aircraft operations. Well-trained pilots struggle with high workloads typical in emergencies requiring contingency response, so it is expected that pilots with less training and experience will be less prepared.

Finding: Encoding well-established contingency management procedures into autonomy will provide a rich baseline capability for automated contingency management in the near term. These procedures can be certified using a combination of existing and emerging certification practices to provide assurance that they will activate and execute safely and correctly. Software-based evaluation tools can be applied to rigorously evaluate autonomy for well-defined deterministic contingency management to reduce the manpower and cost required to use today's certification practices.

Finding: Real-time data processing will be required to enable appropriate autonomous perception, decision-making, and action outcomes in contingency management cases not recognized and matched with established procedures. In such cases, pilots, especially inexperienced pilots, would also be required to ingest real-time data and adapt their situation understanding and decisions in real time. No guarantees of correct response are possible when either autonomy or pilot must learn in real time, yet learning and acting offers a better chance of survival or recovery than shutting down. Machine learning operating in the background might be able to assist in situational awareness (i.e., perception). Decisions informed by machine or human learning can be useful even when correctness guarantees are impossible. Supervisory constraints on learning or adaptive systems can limit machine learning system authority to situations in which automation is essential for success.

Finding: Advanced aerial mobility will typically rely on a variety of real-time data sources for detect and avoid, traffic coordination, and access to data updates—for example, weather and winds. Cyber resilience, the ability for a vehicle or local vehicle group to safely continue a flight operation despite loss or corruption of one or more datalinks or server connections, is an essential component of advanced aerial mobility contingency management.

Recommendation: NASA should conduct research, development, and testing of autonomy for contingency management to support safe advanced aerial mobility.

5

Moving Forward with Advanced Aerial Mobility Implementation

The aviation sector is witnessing the emergence of new vehicle and associated technologies that are poised to redefine the scale and types of operations possible in airspace systems across the globe. These emerging capabilities hold the promise of creating a variety of new applications for aviation that will have far-reaching societal and economic benefits. In order to usher in this era of historic change in aviation, public and private institutions will have to work together in close partnership to facilitate the safe construction, deployment, and acceptance of new advanced aerial mobility technologies, along with supporting infrastructure and regulatory processes.

The opportunities offered by advanced aerial mobility have brought with them a wide range of opinions on how best to proceed with the integration of these capabilities into the national airspace. If these capabilities are to provide benefit to society in the near future, strong public leadership is needed to focus the diverse set of opinions and chart a progressive path forward.

AERIAL MOBILITY PROMOTION, SOLUTIONS DEVELOPMENT, AND ACCOUNTABILITY

New capabilities in flight catalyze new applications and as a result, society demands large increases in the scale and complexity of air operations supported by the airspace system and support for a diverse and evolving set of new applications and mission types. This is a distinct departure from recent decades. Since the establishment of the jet age and commercial airline service, the dominant end market and use case for aviation in the National Airspace System has been well understood and evolutionary in nature. Innovation has predominantly supported driving higher levels of safety and efficiency as commercial aviation scaled.

The Federal Aviation Administration (FAA) originally had a dual mandate to drive increased safety in the National Airspace System as well as to promote aviation's economic growth. This mandate was reduced to the sole mission around safety in the 1990s. In a gradually evolving airspace system and with a relatively static use case, the technological innovation that has been demanded and put in place has built upon the long experience and data accumulated in existing aviation operations. This process has been compatible with a sole-focused deeply safety-oriented culture. However, the rate of progress in fielding even these innovations has been mixed.

The aerospace community now faces a different type of challenge. Systems need to be fielded to explore, design, and ultimately refine new types of flight operations using air vehicles with new capabilities. In the majority of cases, little or no data yet exist for these operations. Without data and without deep experience with the uses and concept of operations, a different approach is needed to satisfy the imperative for the transformation of the airspace system and to do so at the highest levels of safety.

For success, any organization or group of organizations must be aligned to its task. Alignment covers many aspects, including mandate, authority, expertise, and culture. If the United States is to maintain its lead in this new chapter of aerospace, and if it is to capture the full potential of aerial mobility's economic and social benefits, it will have to evolve and equip its crucial public sector roles for the task.

There are precedents that point to the path for success. The Department of Defense, for example, has refined a set of organizations with respective mandates to simultaneously drive the frontiers of research and development with high-risk projects, develop prototype systems alongside industry, commercialize and mature complex systems and solutions as products, and drive operational consistency, safety, and efficiency in the field. Further, some parts of the force that emphasize nimble cutting-edge operations have direct authority to source and adopt new technologies. This in turn serves as an operational test bed for exploration of concepts of operations and refinement for the benefit of the broader force.

Just as the public sector plays a central role in the planning and operation of the nation's defense, the public sector plays a central role in the planning and operation of its airspace system. Without defining the complete set of required roles and responsibilities in line with the nation's objectives for the modern airspace system, it is unreasonable to expect that the nation will achieve those objectives. A new chapter in aerospace as fundamental as the advent of the jet age has begun, and the objectives for the National Airspace System are changing with added dimensions in a more dynamic environment. Meeting these objectives for the National Airspace System is in the national interest, and research will have to be undertaken to define the roles and responsibilities to best meet them and to empower or augment groups within the public sector with the mandate, authority, talent, and culture to succeed.

Discussions with the National Aeronautics and Space Administration (NASA), the FAA, and potential operators and manufacturers have made it apparent that there is no clear entity or organization responsible for stimulating progress and transition to advanced aerial mobility operations. Furthermore, the regulatory and air traffic control (ATC) organizations within the FAA are not set up to manage this transition. The multitude of start-up companies, as well as more established original equipment manufacturers (OEMs) working in this area, do not have the experience or access to structured guidance for defining, developing, and commercializing these new technologies within the existing regulatory structures. Industry and public participants also agree that the certification enterprise is not sufficiently agile or staffed to deal with the pace of innovation.

Finding: The FAA has a sole mandate to promote safety in the National Airspace System and the authority as regulator over the airspace system. NASA has research capability but no authority to regulate or decide on technology implementation for the National Airspace System. This has proven effective at driving exceptional safety but constrains aviation to a modest evolutionary pace.

Finding: Maturing technologies are creating transformational new capabilities in flight that promise to expand the use cases for aviation across the economy and increase the scale of activity in the National Airspace System by orders of magnitude. While associated economic and continued U.S. leadership in aerospace are in the national interest, no entity within the U.S. government has the mandate to promote commercial aviation or the development, adoption, and commercialization of new technologies or applications thereof. Congressional directives to the FAA to integrate new technologies have been episodic and have proven to be suboptimal in driving consistent or timely results.

Finding: Implementing a versatile advanced aerial mobility system with multiple applications and users is a complex, multidisciplinary challenge. No entity, public or private, possesses all the necessary skills. Nor does any single entity currently have sufficient oversight/responsibility to effectively make advanced aerial mobility a reality, while maximizing societal benefits, within the next 3-5 years.

OVERCOMING BARRIERS IN GOVERNMENT, INDUSTRY, AND ACADEMIA

One of the more contentious debates growing among the regulator community revolves around the acceptance and certification of autonomy into the advanced aerial mobility ecosystem. While the potential benefits provided by autonomous vehicle and traffic management systems with authority to make safety-critical decisions in real-time are unquestioned, there is limited understanding about how system certification processes must evolve to assure autonomous systems will be adequately evaluated and tested to meet safety standards. The cost effectiveness to service providers of advanced aerial mobility will be largely dependent on minimizing the need for extensive involvement of highly trained human operators and traffic managers. Multiple vehicle operations with a small human footprint will lead to scalable business opportunity.

Acceptance of autonomous operations at a global scale has been challenging. Regulators have differing opinions on the topic. Some oppose virtually any consideration of completely autonomous air vehicles, embracing the one-pilot-for-one-vehicle approach to operations. Others are more open in their acceptance, by balancing acceptable levels of autonomy in the operating environment with associated risk. Much of the disagreement stems from a lack of empirical data related to autonomous unmanned system operations specific to reliability and the actual risk it presents. Standards development organizations like the International Civil Aviation Organization, other international regulators, and air navigation service providers are taking a very cautious approach to high levels of vehicle autonomy. As a result, primary efforts driving discussion and research on the subject are being undertaken by groups such as Defense Advanced Research Projects Agency, Future Airborne Capability Environment, NASA, and others.

The lack of harmonized view on acceptable autonomy levels is producing a negative impact on advancing overall development of advanced aerial mobility. Hardware and operational requirements for highly automated vehicles will drive the certification and operational approval process. Assuming that unmanned air vehicles will generally have to look and act like currently certified manned aircraft, much work remains to ensure that highly automated advanced aerial mobility vehicles comply with emerging regulations and standards.

Adapting currently available, certified automation technology is challenging from a number of perspectives. Aircraft supporting advanced aerial mobility operations may have significant size, weight, and power limitations. Adding certified hardware to many of the platforms would have significant economic impact related to reduction in payload capacity and add to the overall cost of vehicle development. A number of innovative technology start-up companies are proposing viable solutions that address these concerns (see Figure 5.1). The off-the-shelf nature of these new solutions, however, presents certification challenges owing to the lack of availability of performance and reliability data.

The level of acceptable increases in autonomy will have an impact on other elements of the advanced aerial mobility system. For example, the ongoing debate over the need for protected frequency spectrum for vehicle command and control could be changed by increasing acceptance of greater levels of autonomy. If the command and control link to the vehicle is limited to health monitoring or management of off-nominal situations, the need for a secure continuous link and associated bandwidth could be minimized.

More autonomy can have an impact on operator/crew training requirements. Highly automated vehicles reliant on artificial intelligence and other software and firmware solutions can reduce knowledge, skill, and ability requirements for flight crew certification. There may be other human factor issues associated with autonomy requiring further research.

Last, highly automated vehicles will impact how airspace is managed. The ability to accept autonomous conflict resolution as part of future detect and avoid (DAA) performance standards will have to be explored. Establishing air traffic management (ATM) procedures to accept autonomous maneuvering, flight planning, and contingency management will have to become a near-term priority in the overall autonomy conversation.

Finding: The success of advanced aerial mobility will depend on the ability to create scalable business opportunities. Reduction in the "human footprint" associated with operationalizing advanced aerial mobility services will be essential.

Finding: The efficiencies gained by the adoption of advanced aerial mobility in passenger and freight services will be greatly enhanced by maximizing vehicle autonomy.

Finding: There is still concern expressed by regulators over expansion of automation and autonomy in unmanned aviation.

FIGURE 5.1 An artist concept of a Bell Nexus aircraft over Dallas, Texas. SOURCE: Copyright Bell, 2020.

Finding: NASA will be conducting workshops to identify the risks associated with expanding autonomous operations.

Finding: A successful advanced aerial mobility system will need to interact within relevant federal, state, and local regulatory regimes. These include concerns and potential mitigating actions about liability, noise, construction, infrastructure, flight paths, energy, environmental issues, ground traffic, equity, and other issues. Existing state and local regulatory regimes have jurisdiction and authority to impede or prohibit several aspects of an advanced aerial mobility system.

Finding: Without regulatory certainty, advanced aerial mobility systems will develop in an ad-hoc manner, likely with private point-to-point systems instead of open many-to-many systems. This would establish suboptimal path dependence for future growth and development in the advanced aerial mobility system.

Finding: The following issues are important for expanding autonomy and the use of adaptive systems in advanced aerial mobility:

- Requirements for dedicated safety spectrum for advanced aerial mobility command and control communications;
- Operationalizing autonomous collision avoidance maneuvering;
- Human factors associated with increased vehicle autonomy;
- Impact on overall ATM, including unmanned traffic, in all classes of airspace;
- Approval of the software within such systems;
- Need to develop best practices for advanced aerial mobility regulatory regime and model vertiport siting plans, including land use guidance;
- Advanced aerial mobility system policy recommendations to overcome barriers in state and local governments; and
- Standardized common vertiport components and recharging/refueling infrastructure as well as models for competitive development, deployment, and operation of distributed advanced aerial mobility infrastructure.

FLIGHT TESTING AND RAPID DEVELOPMENT ENVIRONMENTS

Flight testing plays an integral role in successfully building, certifying, and fielding new aerospace systems. Developmental flight testing assesses the airworthiness of the vehicle and explores the boundaries of its flight performance envelope. Operational flight testing puts an air vehicle through extensive scenarios relevant to its intended application to understand how the vehicle, people, and broader systems and infrastructure best work together to ensure safe and efficient operations.

Advanced aerial mobility increases the demand for developmental flight testing. According to *Electric VTOL News* (a media arm of the Vertical Flight Society), 191 passenger electrically powered vertical takeoff and landing (eVTOL) air vehicle concepts are under development (as of July 20, 2019). Additionally, a large number of both small and large cargo drone aircraft are under development that will also go through a certification process. Flight testing for well-understood rotorcraft, for example, typically exceeds 1,000 flight hours. The novel and complex configurations of transitioning VTOL aircraft, in addition to their electric propulsion and flight control systems, can drive up the flight-testing hours required. This is particularly the case during the early days when engineers, standards bodies, and regulators are less familiar with the technology and when the general configurations of different aircraft designs remain highly heterogeneous.

Advanced aerial mobility also increases demand for operational flight testing. In recent decades, the end applications for which aircraft were developed were very well-understood. Whether commercial aviation, first responders and public services, or industrial applications such as offshore oil services, a great deal of experience and data were already in-hand to guide aircraft development and operational integration.

A key aspect of advanced aerial mobility is that it enables new applications for which aircraft were previously not feasible. The operational details of what works best for these new applications, how aircraft are best employed in them, how ground infrastructure is best configured, and how these pieces integrate as a broader system and as part of the overall national airspace system, is not well understood. Further, the full scope of the applications themselves is not explored or well understood. This drives a far greater demand for operational flight testing than exists today.

Modern approaches to safety assurance increase the demand for flight test and operations data to identify and mitigate safety risks before accidents happen. Historically, commercial aviation has taken a forensic approach to safety assurance. For example, a midair collision in 1956 over the Grand Canyon led to instantiation of the first ATC. Structural failures in flight led to design remedies. The aviation industry learned from accidents and modified the airspace system to ensure they did not happen again.

Today, safety assurance means identifying and mitigating risks before they happen through analysis of data. This works well for existing applications where large quantities of data are available. However, for emerging applications such as urban air mobility (UAM), cargo transport, or autonomous drone operations, the data to assess and mitigate safety risks do not yet exist. The need to generate these data in support of safety assurance drives greater demand for flight testing capabilities and facilities able to support this type of ongoing flight testing and data generation under a spectrum of controlled scenarios.

Increased flight test capabilities that are integrated with a vehicle or operations development process accelerate development and improve outcomes. With the ability to easily collect robust test data, analyze them, and act on them with confidence, better design decisions are made, design iterations shorten, and technical solutions converge earlier in the project. This has a compounding effect on accelerating progress while also creating the capacity for more diverse concepts and applications of the technology to be pursued.

Overall, the challenges and opportunities are to reduce the complexity of working with and integrating the technologies transforming aviation and to create a rapid development environment that will shorten the design iteration loop and enable faster progress while providing the data to support certification and creation of operating standards (see Figure 5.2).

There is a lack of suitable flight-testing capability today. Testing of unmanned or autonomous flight must, for the most part, take place under special regulatory accommodation. Unlike manned aircraft that can perform flight testing in the national airspace alongside other traffic, these aircraft must be tested under special conditions, which in most cases requires flight testing at purpose-built test ranges or, in some cases, in restricted airspace.

Several large military test ranges exist within the United States that have access to restricted airspace and are used for flight testing of aircraft. Use of these ranges requires coordination with the military and typically requires a military interest in the mission being flown for the vehicle under development. The facilities available are generally extensive and well-developed, with infrastructure, workspace, and personnel accommodation readily available.

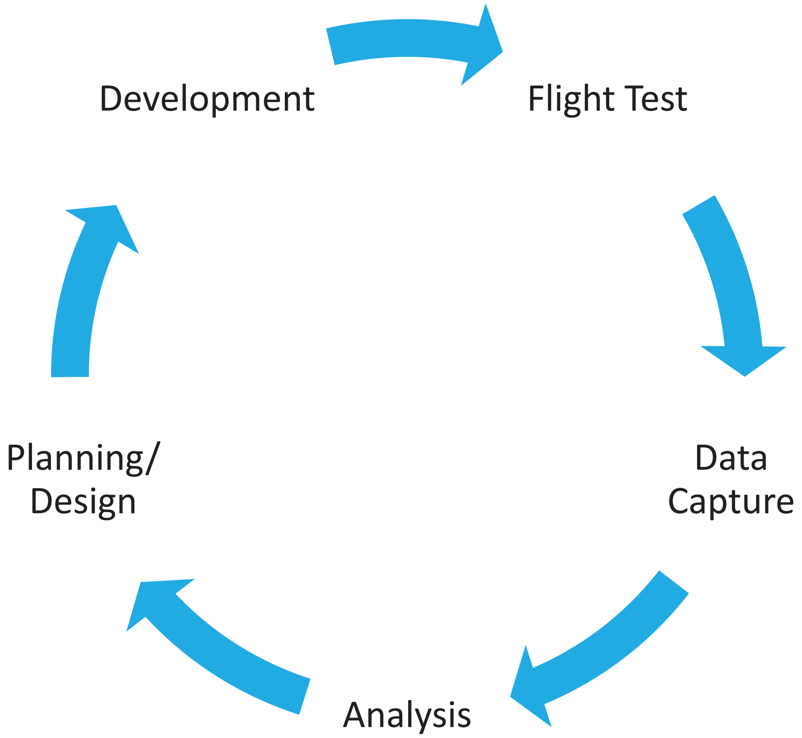

FIGURE 5.2 The design iteration loop for advanced aerial mobility systems.

Availability of military test ranges is limited due to competing operations on the site, and conducting tests at military ranges requires extensive advance planning, preparation, and paperwork. Generally, the process of working at a military test range is rigid, allowing limited flexibility to rapidly iterate the development and test plan in response to learnings generated from the testing. While the public is generally excluded from military test ranges, many government personnel are present, and it is difficult for a commercial company to test its vehicle in privacy.

Looking beyond military ranges, no suitable test airspace is available on a dedicated basis in the United States to aerial mobility developers focused on commercial applications. Further, the industry also needs testing capability for infrastructure, surveillance, communications, airspace management, and operations systems.

This demand for testing implies a need for locations where companies can do extended testing and development with ongoing consistent access to airspace; the ability to access and modify infrastructure on the ground under the airspace to support operational flight test scenarios and application development; surveillance, communications, and telemetry data acquisition infrastructure; and overall ease of access to the test range and ease of working at the range.

An investment in the creation of test facilities, including the necessary regulatory accommodations to make them effective, should yield a high return in the form of accelerated development, more air vehicles and applications being commercialized, and improved U.S. competitiveness in this new chapter for the aerospace industry.

Recommendation: NASA, in coordination with the FAA, should make allocations of facility resources and airspace and regulatory accommodations to establish a continuous flight test capability that supports rapid development of the following:

- **Air vehicles;**
- **Flight operations practices;**
- **Surveillance and communications technologies/networks;**
- **ATM systems, leveraging Unmanned Aircraft System Traffic Management construct and lessons;**
- **System-wide management systems;**
- **Noise reduction technologies and operations; and**
- **Ground infrastructure specific to various applications.**

This flight test capability should be designed to enable industry to innovate and commercialize its platforms/applications more rapidly. This effort can build on the progress and assets already in place from existing test range programs.

The committee recognizes that in the past elaborate government ranges incurred great expense and were also underutilized. The concept the committee envisions is based on the view that the difficulty of constructing a true urban environment physically represented and the permission to fly medium and large Uninhabited Aerial Vehicles are creating a barrier larger than most companies can overcome. The committee envisions this joint facility not as purely a government range at government expense but rather fostered by government input and funded jointly. Both industry and governments will be involved in making advanced aerial mobility succeed. But this success will require more than simply government serving as a regulator or gatekeeper. There are opportunities for private entities and government organizations to cooperate to ease and even accelerate the transition to development and public acceptance of advanced aerial mobility.

PUBLIC-PRIVATE COOPERATION AND URBAN AIR MOBILITY SYSTEMS

The development of an ecosystem supporting the advancement of multimodal UAM will present challenges not anticipated in traditional aviation pursuits and is probably the most difficult aspect of advanced aerial mobility. The complete list of anticipated societal advantages to UAM advancement have yet to be identified. However, with any advancing technology, challenges emerge that may require extensive change to accepted practice. Routine operation of air vehicles supporting UAM will have operational differences and characteristics not currently found in air transportation or personal aviation requirements. UAM will encompass vehicles propelled by alternative power sources, capable of operation to and from confined urban areas independent of the need for traditional runways. Air vehicles will likely operate with a high degree of automation over defined routes utilizing performance-based navigation. These innovations will allow UAM service providers to successfully scale operations and maximize benefit to the consumer.

It should be clear that advanced aerial mobility service providers need support from public organizations to advance regulatory, standards, and infrastructure elements needed for the economic growth of emergent air operations. The situation seems ideal for the establishment of a public-private partnership focused on facilitating implementation of advanced aerial mobility. There are successful examples of this approach within the aviation sector. The committee learned about a successful public-private partnership, dubbed the Commercial Aviation Alternative Fuels Initiative, that was used to facilitate the implementation of sustainable alternative fuels in commercial aviation. In this partnership, the FAA, manufacturers (i.e., fuel producers and OEMs), operators (i.e., airlines and airports), and research establishments contributed core competencies to assist in the sustainable adoption of alternative fuels. Forging a new path, the group worked with ASTM to develop standards that would be accepted by the FAA rather than looking to the FAA to lead the certification of new fuels. The various entities did not choose “winners.” Rather, processes were established by which various fuels could be approved for use. A similar approach, working with any standards development organization, could work very well to facilitate implementation of advanced aerial mobility.

One area that may benefit from a public-private partnership is finding solutions to the establishment of embarkation and deembarkation facilities for advanced aerial mobility. With the expanding urban population, the availability of prime real estate to construct new facilities designed to support UAM will decline. Costs associated with land acquisition in urban areas will rise and, as a result, will negatively affect UAM growth. The public advantages of UAM will be dependent on convenient access to vertiports and heliports specifically configured to support the new modes of air transportation. Key to addressing this issue may be repurposing existing infrastructure in strategic locations affording the best public access. There are also emerging models where the vehicle operator controls the infrastructure as well—in other words, the infrastructure will be fundamentally private, not publicly accessible.

Traditional airports are increasingly under scrutiny by state and local officials amid complaints that they are nonessential and a public nuisance. FAA statistics show that in 2017 there were approximately 5,104 public airports in the United States, down from 5,145 in 2014. Conversely, the number of private airports has increased over the same period from 13,863 to 14,263.[1] Some high-profile municipal public airports ideally located to support UAM in densely populated areas either have closed or are under threat. Examples include Meigs Field in Chicago, Blue Ash Airport in Cincinnati, and Bader Field in Atlantic City. Others under threat of closure include Santa Monica and Van Nuys Airports in the Los Angeles basin, Allentown Queen City, Bakersfield Municipal in California, and St. Clair Regional Airport in Missouri.

Closure of public airports can be challenging to municipalities if the facility has received federal funding for their operation. Airport Improvement Program funding agreements mandate that airport owners comply with all federal obligations and that any airport revenue (including sale of property) be invested in a replacement airport, reinvested in airport-related projects, or returned to the Airport and Airway Trust Fund. These requirements make airport closure unattractive to many for obvious reasons but do not lessen public pressure to do so. Repurposing existing airports to exclusively support UAM operations could mitigate much of the public outcry. The location of many of the threatened airports makes them an ideal hub for UAM transportation of passengers and cargo to and from major airports or other high-traffic urban locations.

Traditional public and many private airports have many of the components necessary for UAM operations. Established instrument arrival and departure procedures, security, and aircraft and passenger servicing facilities will be essential components to any UAM service provider and are readily available at most airports. With some modification, much of this existing infrastructure can be modified to accommodate the emerging UAM market.

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[1] A private airport is any airport not open to the public. A public airport (according to 14 CFR §152.3) means “any airport that (1) is used or intended to be used, for public purposes; (2) Is under the control of a public agency; and (3) Has a property interest satisfactory to the Administ,rator in the landing area.” See FAA, “Airport Categories,” https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/categories/.

Because most future UAM aircraft will have capabilities not requiring traditional runway configurations, other alternatives to repurposing traditional airports exist. The rapid decline of large tract shopping facilities resulting from increasing popularity of online shopping and timely ”last mile” delivery of products has increased the availability of the associated real estate footprint for alternative uses. Conversion of shopping centers and malls to UAM transportation hubs could be a viable alternative to new construction or land acquisition.

The FAA is currently undertaking a study (solicitation/contract #33063) requesting details on vertiport design and capability to support future UAM requirements. The purpose of the request for information is to solicit information from eVTOL aircraft designers/manufacturers related to their technical and design approaches and the vehicle's landing and takeoff capabilities, including information regarding eVTOL facilities that the designer/manufacturer has. The information will be used to facilitate the development of minimum standards and guidance for the design and operation of eVTOL facilities that support civil eVTOL aircraft.

Finding: Advancing UAM will likely require new infrastructure or modification of existing airports and heliports to serve the unique needs of the emerging air vehicle performance and configuration requirements.

Finding: Construction of new heliports or vertiports will be costly and complex due to a lack of clarity in regulatory requirements for public facilities.

Finding: There are tens of thousands of underutilized airports and large tracts of abandoned real estate throughout the country that could be converted for use by UAM service providers.

Finding: FAA is soliciting industry through a formal request for information to create standards for vertiport design.

Finding: Infrastructure enabling a UAM system will include vertiports, vehicle hangar and maintenance areas, and associated recharging/refueling infrastructure. A robust UAM system would have multitudes of vertiports serving a metropolitan area; hence, UAM infrastructure will necessarily be distributed rather than centralized.

Finding: Public-private partnership arrangements could be used to enable growth of distributed UAM infrastructure in a metropolitan area, while enabling this infrastructure to be a common carrier for different types of vehicles from different firms. This would enable competition and innovation in the UAM system.

Recommendation: A public-private partnership should be established to facilitate advanced aerial mobility implementation in a virtual environment to deliver as a near-term capability to define mobility systems and infrastructure requirements. This virtual environment should complement physical flight and operations testing. The partnership should be coordinated by NASA, in collaboration with the FAA and with coordinated allocation of responsibility among the FAA and other relevant agencies, industry (original equipment manufacturers and operators), and standards development setting organizations. For example, the group could focus on developing guidelines and solicitations for advanced aerial mobility infrastructure deployment.

NASA's National Campaign program is taking a first step in accomplishing this, and the committee believes that NASA should continue to pursue these goals. The value proposition for industry is that identification of technical hurdles and their elimination will support regulation and standards development, ultimately leading to certification.

STANDARDS-BASED PROTOCOLS AND INTERFACES TO MOBILIZE THE PRIVATE SECTOR AND ACCOMMODATE RAPIDLY EMERGING APPLICATIONS OF FLIGHT

Humanity has been working to create larger and more efficient physical-world systems, leveraging the proven power and productivity benefits of software and data. Transportation systems are a main area of this research, given the increasing strain they are experiencing as they are scaled up. Examples of software driving new transportation systems in various ways include ride-sharing platforms, autonomous cars, the modern National Airspace System, and future UAM operations.

Transportation systems today are heavily dependent on human operators working throughout to enable the basic functions of moving objects and vehicles through the physical world. This is necessary because human operators have key capabilities that enable safe functioning of these very complex systems, including perception, the ability to anticipate behavior, a sense of context, human judgement, and self-preservation instinct.

However, humans also have their limitations. In a three-dimensional (3D) flight environment, they are able to safely track and avoid only a very limited number of other vehicles in the vicinity, severely limiting system density and scale. The free-form openness of the flight environment also increases complexity and workload as compared to a two-dimensional (2D) path-based linear network where the defined structure of the lanes reduces the potential choices and anticipated moves others nearby may make. The 2D systems are less complex than 3D systems. Last, human traits such as fatigue and lapses in judgement are limits that cause accidents and fatalities.

Humans operate satisfactorily in linear transportation networks. In nodal networks where routes are less structured, more training and professionalization has been required. The only nodal transportation networks that have been fielded have been sparse, however, and those have required extensive operator training.

The movement toward high-density nodal networks exceeds the capacity of human operators. Therefore, the industry must automate the high-density nodal networks that it wants to build and that represent the future of transportation systems.

The forefront of technology's enablement of future transportation is to transfer the roles humans play into software. Whereas a human-driven system decentralizes decision making across the human operators, debate continues as to what degree a software-automated system would change this, mixing centralized control of movements with distributed decision making and actions.

The National Airspace System is a nodal transportation network that has seen increased density over time but that remains a relatively sparse network even today. Humans operate the vehicles flying throughout this network as well as manually coordinate and direct air traffic to ensure safe operations.

The National Airspace System today is the result of decades of evolution, starting with free flight navigation and migrating to procedure-based separation, then to radar and radio navigation-aid supported control systems, sophisticated terminal area positive control procedures, and, most recently, Global Positioning System-enabled precise navigation procedures. Yet, this system still depends on human operators to play key decision-making roles throughout routine operations. Human eyes remain the most important and capable positioning and collision avoidance capability in the system. Human judgment remains the most capable risk assessment and safety mitigator in the system.

As the industry moves to higher-density air transportation systems that require automation of these human functions, the software that manages them must make a leap in capability compared to today. Data characterizing the state of the system must increase orders of magnitude in fidelity. Systems to monitor the ongoing quality and reliability of that data must be implemented. Further, the software system now has to take over the judgment and decision-making functions, detecting risks, making assessments, and taking mitigating actions.

This leap in capability is a stark departure from recent evolutionary progress in the National Airspace System. The design of this type of system is distinctly new and different and represents one of the first instances of a generalized capability that humankind will build across many applications in the coming decades.

A challenge that the broader technology community faces today is to embed software and automation into physical-world systems, such as transportation, and thereby to bring the speed, precision, and proven productivity benefits of the digital world into these systems.

However, the physical world is much more complex and varied than the pristine, controlled structures of pure digital data systems. The physical world must be sensed using imperfect tools whose performance can vary greatly based on the environment. Signal and noise must be separated, and the underlying data themselves can sometimes lack the full information fidelity to make decisions.

In the process of sensing and modeling physical world systems, practitioners have evolved the idea of creating validated digital models of the physical system, often called "digital twin." A digital twin is a model that is designed to accomplish a specific, limited, engineering purpose—for example, predictive maintenance. It is codesigned with the physical system that must be instrumented to provide behavior and performance information to be delivered intermittently to the model's database—but only that information that is required for the purpose of the model. Digital twins are already proven to be viable for predictive maintenance. A digital twin for that purpose need not receive updates second by second. Maintenance is typically only performed when the system is out of service and on the ground. Digital twins have proven to be a viable engineering tool for select purposes, and those purposes are important in aviation.

Such models allow developers and operators to analyze system behaviors in various conditions and with various failure modes to generate the data necessary to assess end-goal objectives. For the airspace system, the digital model can serve multiple objectives including safety assurance, system performance, failure tolerance/resilience, resource efficiency, and accommodating new applications and air operations. The use of “digital twins” is an important part of modern digital control and system development technologies and thus can be used to guide airspace design and vehicle integration in urban settings.

However, the digital model is constantly at risk of losing coherence with its physical ground-truth counterpart. Divergence can lead to digital model performance degradation and loss of validity. Underlying this is the fact that regardless of whether the software model keeps pace, the state of the physical world moves forward through time. In the aviation case, aircraft move forward through the airspace, the weather changes, and operators take action every second. For this reason, metrics to establish and continuously track digital model validity are essential. In addition, this continuous coherence requirement also establishes the need for the physical system to produce its own data as a normal system output in suitable form to allow the digital modal validity tracking.

Underlying this is the fact that regardless of whether the software model keeps pace, the state of the physical world moves forward through time. In the aviation case, aircraft move forward through space, the weather changes, and operators take action every second. The physical ground truth always moves forward in time.

As people build software into tight integration with the physical world, and safety-critical transportation systems in particular, questions arise as to how to ensure that the software system maintains an accurate reflection of reality. Detecting and responding to a divergence or degradation is also essential. Addressing these issues is complex and application specific but begins with the data—how data are collected, stored, and used. NASA’s SMART-NAS test bed could be used to assess digital twin viability.

To build a digital-physical system capable of safety-critical decisions over a wide geospatial and temporal scale, it is very important that it operate on high-quality data and moreover that it be managed in a system carefully designed for the purpose.

Correctly designing a universal coordinate system for all data points is crucial, as all functionality and system operations depend on it. A goal of the common coordinate system standard should be the generation, transmittal, sharing, and analysis of geospatial data on a system-wide basis.

Careful design and implementation of the time dimension, both for data collection and fusion as well as for downstream processing, is critical. A goal should be to align all components across the airspace system to a common and synchronized time standard, given the crucial role timing plays in coordinating and executing safety-critical flight operations.

Along with the spatial coordinate system, the data store has to be designed around the time dimension from its very foundation. Associating data that are nearby both in spatial as well as temporal terms has to be efficient and flawless while operating at maximum scale and throughput performance.

Every data point, whether a vehicle position observation, a vehicle health reading, a weather observation, or anything else, will be associated with spatial and temporal data.

Finding: Technology’s impact on flight is leading to a significant expansion of use cases for flight across the economy. This proliferation of uses will lead to rapid growth in demand for airspace system management services, with varying requirements for each application that are hard to forecast and design for today.

Finding: Increasing automation of aircraft and of the broader National Airspace System is necessary to enable system-scale and higher density use of airspace while providing increased levels of safety.

Finding: Automation will require vastly increased data capture, sharing, and analysis across a heterogeneous and geographically dispersed system of systems. In some instances, these data will be produced, shared, and consumed in near real time.

Finding: There is a need for a live, virtual, constructive capability to assess digital twin options.

DATA QUALITY ASSESSMENT PROCESSES

Monitor processes to continually assess and record metadata as to the quality of incoming National Airspace System observation data is necessary to enable downstream analytics and decision processes that yield a safe outcome while accounting for the limitations of incomplete or low-quality data. This metadata can include system configuration information, subsystem component health status, key environmental and performance metrics, and other application-specific data.

To adjust their behavior when data degrade, systems must know the quality and completeness of the incoming data streams during operation. Based on this quality, they must adjust decisions and actions taken based on the limitations of the available data.

When data degrade, system conservatism increases in order to maintain risk levels and safety standards. An example of this could be increased aircraft spacing when and where high-fidelity data are unavailable. In this way, the software system can function effectively with the physical world system under varying real-world conditions.

This foundation of data can be the basis for functionality that delivers performance while also ensuring safety fallbacks (i.e., methods specific to the application) during degraded conditions.

Finding: Even today, small-scale operational test scenarios in the drone community are revealing the challenges of system-wide state and metadata capture, component performance and health, and generation of complete and consistent scenario operations data that support the full set of intended analyses and that are like-for-like comparable to future data generated in other scenarios or at other locations. These challenges are holding back the industry and regulators from generating sufficient safety assurance data to support rulemaking allowing expanded complex flight operations.

REAL-TIME DISTRIBUTED COMPUTING

Real-time processing is a form of computing that processes data within a guaranteed time frame. Building on prior work, real-time processing technology needs to be adapted and expanded to meet the unique needs of high-scale airspace system management. A goal should be to identify approaches to data communications that guarantee timely transmission of safety-critical data and built-in management of time-related aspects of every data point across the system.

Real-time processing against a large and diverse distributed data store must be demonstrated, both in nominal and off-nominal scenarios. Protocols to demonstrate and enable this capability at scale will need to be agreed upon.

MOBILIZING THE PRIVATE SECTOR

Emerging advanced aerial mobility applications will lead to rapid growth in demand for airspace system management services, with varying requirements that are hard to forecast and design today. The pace of this demand growth will likewise outrun the ability of any monolithic system design to adapt and grow to meet the need, particularly if solely overseen by the public sector.

It is thus of prime importance to enable and mobilize the private sector to innovate on higher performance airspace management technologies in close collaboration with the public sector. As technology history has shown, this can be done, in part, with the public sector leading, and rapidly transitioning, research on system topology and protocols, data formats, and data exchange standards necessary for interoperability and transparency and giving private sector participants certainty as to what objectives to innovate toward.

A standards-based approach to building open protocols for networking (e.g., TCP/IP) and exchange of data (e.g., HTTP) enabled a proliferation of product types and application of the standards to a wide spectrum of uses. Likewise, in future aviation, many applications will emerge with different performance demands and usage densities. As in wireless telecommunications, some areas will experience more dense usage than will others. The telecommunications industry has built adaptive infrastructure and services to accommodate areas of both sparse and dense usage. Datalink and interface standards are foundations of safe high-density adaptive airspace and traffic management. Additional position tracking and sensing assets can be deployed in areas of high density and can be seamlessly incorporated to offer the fidelity necessary to meet risk thresholds and reduce vehicle spacing requirements.

Finding: The pace of demand growth will outrun the ability of any monolithic system design to adapt and grow to meet the need, particularly if solely overseen by the public sector. It is thus of prime importance to enable and mobilize the private sector to innovate on higher performance airspace management technologies.

Finding: As technology history has shown, this can be done, in part, with the public sector leading the research on the system topology and the protocols, data formats, and data exchange standards that define the broader system and giving private sector participants certainty as to what objectives to innovate toward.

Finding: Data exchange for advanced aerial mobility is diverse in content, size, and real-time update requirements. DAA and separation assurance applications require a common geospatial framework for aircraft state updates as well as communicating intent and ATC directives. Geographic information system maps of terrain and man-made infrastructure compatible with vehicle sensor systems (e.g., lidar, vision) must be established along with procedures to ingest real-time updates as new obstacles (e.g., construction crane) and ground-based risk factors (e.g., occupancy and road vehicle traffic) are reported.

Finding: The pace of technology adoption in the public sector is slowed by the perception of high adoption costs and resistance to change—for example, Automatic Dependent Surveillance-Broadcast. Meanwhile, the public sector has already standardized and deployed data exchange protocols with vastly more resilience, bandwidth, and versatility at lower per unit cost. Success with large-scale advanced aerial mobility depends on migration to high-bandwidth standardized data exchange solutions.

Finding: No public entity exists today with authority to establish and manage data standards for aviation data exchange. Standing up such a group would facilitate both the creation and evolution of data content and formats as advanced aerial mobility technologies and operations evolve.

Recommendation: A working group comprised of NASA, industry, academia, and the standards development organizations should prioritize research on the protocols, data formats, and data exchange standards that support advanced aerial mobility vehicles in a geospatial real-time system supporting safety-critical operations across the National Airspace System. The intent should be that the tools developed will provide the necessary clarity to catalyze and enable commercialization of system components by industry.

CONCLUSION

This study was commissioned by NASA, and the committee concluded that NASA has an important role to play in this emerging field, but it is not the most important role.

Finding: The FAA will play the most important government role in enabling advanced aerial mobility, with support from state and local governments as well.

Throughout this report the committee has highlighted key findings that have been identified and has proposed recommendations as to how NASA might seek to proactively address technical and structural gaps. Driving progress in these topics is crucial because they may manifest themselves as critical risks and exposures in the pursuit of advanced aerial mobility. In addition to this feedback, the committee feels that there remains an overarching unmet need that it believes must be considered at a systematic macro-level in order to be sufficiently addressed. This need centers on virtual certainty that the pace of advanced aerial mobility demand will outrun the ability of any monolithic system design to adapt and grow to meet the need, particularly if solely overseen by the public sector. It is thus of prime importance to enable and mobilize the private sector to innovate on higher performance airspace management technologies.

Appendixes

A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine will convene an ad hoc committee to assess the feasibility of a safe and efficient urban air mobility (UAM) system. In terms of general definition and concept of operations, the committee will consider UAM to be a system for air passenger and cargo transportation within a metropolitan area (including operations over densely populated urban areas), with vehicles ranging from small drones to passenger aircraft with electrically powered vertical takeoff and landing (eVTOL) capabilities. For both manned and unmanned aircraft, the study will focus on a system vision (including interface/integration into broader air transportation systems, ground transportation systems, and smart city systems generally), barriers, entrepreneurial approaches, and research projects that are particular to operation in uncontrolled airspace over metropolitan areas. In particular, the committee will:

1. Consider
   - Essential characteristics of a UAM system.
   - Key barriers to developing and deploying a UAM system that demonstrates the essential characteristics.
   - Risk-based approaches to addressing key barriers, so that evolutionary market development can occur, from market emergence with limited operations, through growth and expansion as safety cases and community acceptance allows, and last to mature operations in urban areas.
   - Progress in related areas, such as the development and implementation of standards and operational capabilities to enable UAM operations, the UAM Traffic Management system, cybersecurity, and urban planning.
   - Highly entrepreneurial approaches, including nonaviation industry entrants, that are relevant to UAM market development.
2. Prepare a report that will:
   - Develop and discuss a recommended national vision for UAM.
   - Identify and prioritize by group the key technical, economic, regulatory, and policy barriers to achieve the vision.
   - Assess the potential impact of highly entrepreneurial approaches, including those that could be implemented by nonaviation industry entrants, in achieving the vision.
   - Recommend key research projects that NASA, other government agencies, industry, and academia could employ to overcome the barriers and facilitate likely approaches to achieving the vision.
   - Assess the potential and benefit for a public-private partnership in addressing the technical, economic, regulatory, policy, and other related (e.g., urban planning) requirements.

B

Committee and Staff Biographical Information

NICHOLAS D. LAPPOS, *Chair*, is a senior technical fellow for Advance Technology at Sikorsky. Mr. Lappos is also chair of the board of directors of the Vertical Lift Consortium (elected in 2010 and 2012), an industry consortium established to work collaboratively with the U.S. government to develop and transition innovative vertical lift technologies to rapidly and affordably meet warfighter needs. He was elected to the Academy of Distinguished Engineering Alumni of the Georgia Institute of Technology in 2004 and awarded the Sir Barnes Wallis Medal by the U.K. Guild of Air Pilots and Navigators in 2013. Mr. Lappos is an honorary fellow and technical fellow of the American Helicopter Society (2013) and received the Frederick Feinberg Award as most outstanding pilot and the Society of Experimental Test Pilots Tenhoff Award (1988). Mr. Lappos holds 23 U.S. patents and three FAI world speed records. He has authored numerous technical papers for the American Helicopter Society, the Royal Aeronautical Society, and SAE International, has written articles for magazines such as *Rotor and Wing* and *Interavia*, and has a regular column in *HeliOps Magazine*. Mr. Lappos is a U.S. Army Vietnam veteran, and served as a Cobra attack helicopter pilot. He was awarded the Bronze Star and the Republic of Vietnam's Cross of Gallantry. Serving as a test pilot for Sikorsky for more than 27 years, he has flown more than 70 different helicopter types. With more than 7,500 hours flight time, Mr. Lappos served as chief research and development test pilot for more than 12 years. He has served on numerous technical committees for the National Aeronautics and Space Administration (NASA), the American Helicopter Society, the Federal Aviation Administration (FAA), and the North Atlantic Treaty Organization's (NATO's) Advisory Group for Aerospace Research and Development committees and working groups. Mr. Lappos has participated in the development of serval flight systems such as the S76, UH-60, RAH-66, ABC, Fantail, Shadow, Fly-by-Wire demonstrator, CH-53E, and S92. He was the program manager for the S-92 program during its development, certification, and introduction into production. During that time, the National Aeronautic Association awarded the S-92 Industry Team the Robert J. Collier Trophy. Mr. Lappos has a B.S. in aerospace engineering from the Georgia Institute of Technology. For the National Academies of Sciences, Engineering, and Medicine, he has served on the Aeronautics and Space Engineering Board (ASEB), the Aeronautics Research and Technology Roundtable, and Aeronautics 2050: A Workshop.

ELLA M. ATKINS is a University of Michigan professor of aerospace engineering, associate director of the Robotics Institute, and director of the Autonomous Aerospace Systems (A2SYS) Laboratory. Dr. Atkins previously served on the aerospace engineering faculty at the University of Maryland, College Park. Dr. Atkins is editor-in-chief of the American Institute of Aeronautics and Astronautics (AIAA) *Journal of Aerospace Information Systems (JAIS)*, an AIAA fellow, an Institute for Electrical and Electronics Engineers senior member, a small public airport owner/operator (Shamrock Field, Brooklyn, Michigan), and a private pilot. She was a member of the Institute for Defense Analyses Defense Science Studies Group. Dr. Atkins holds a B.S. and an M.S. in aeronautics and astronautics from the Massachusetts Institute of Technology (MIT) and M.S. and Ph.D. in computer science and engineering from the University of Michigan. She has served on the National Academies ASEB, the Committee on Autonomy Research for Civil Aviation, the Aeronautics Research and Technology Roundtable, and the Committee for the Review of NASA's Aviation Safety Related Programs.

JAMES G. BELLINGHAM is the director of the Center for Marine Robotics at the Woods Hole Oceanographic Institution (WHOI). Dr. Bellingham arrived at WHOI from the Monterey Bay Aquarium Research Institute, where he was director of engineering and recently chief technologist. Dr. Bellingham was founder and manager of the Autonomous Underwater Vehicle Laboratory at MIT and co-founder of Bluefin Robotics, a Massachusetts-based company that develops, builds, and operates autonomous underwater vehicles (since acquired by Battelle). He recently served as a member of the Naval Studies Board committee that helped prepare the report *Mainstreaming Unmanned Undersea Vehicles into Future U.S. Naval Operations*.

ATHERTON A. CARTY is the director of Enterprise Technology Roadmaps at Lockheed Martin. A technical executive leader within the Lockheed Martin Advanced Development Programs (ADP) organization, also known as "The Skunk Works," Mr. Carty is responsible for developing and maturing key enabling technologies and transitioning them to address critical customer needs. ADP's Enterprise Technology Roadmaps organization includes Air Vehicles, Mission Systems, Survivability, and Revolutionary Technologies and Emerging Concepts portfolios focused on providing enabling technology in support of both current and future programs. He is an AIAA associate fellow and received the Lockheed Martin NOVA and Aerostar awards. He earned a M.S. in mechanical engineering from George Washington University's Joint Institute for the Advancement of Flight Sciences at the NASA Langley Research Center.

DANIEL DeLAURENTIS is a professor of aeronautical and astronautical engineering at Purdue University. Dr. DeLaurentis also serves as the director of the Institute for Global Security and Defense Innovation at Purdue University. His research is focused on the development of foundational methods and tools for addressing problems characterized as system-of-systems in the context of Next-Generation Air Transportation Systems, especially including the presence of revolutionary aerospace vehicles, new business models, and alternative policy constructs. Dr. DeLaurentis has received the C.T. Sun Research Award and the Kevin Corker Award. He earned a Ph.D. in aerospace engineering from the Georgia Institute of Technology. Dr. DeLaurentis has previously served on the National Academies Panel on Engineering, Mathematics, and Computer Sciences.

NANCY G. LEVESON is a professor of aeronautics and astronautics at MIT. Dr. Leveson conducts research on the topics of system safety, software safety, software and system engineering, and human-computer interaction. Dr. Leveson received the Association for Computing Machinery Allen Newell and the Sigsoft Outstanding Research Awards for computer science research, and the AIAA Information Systems Award for "developing the field of software safety and for promoting responsible software and system engineering practices where life and property are at stake." Recently she was awarded the 2020 IEEE Medal for Environmental and Safety Technologies. She is the author of two books on system safety. Dr. Leveson received a Ph.D. in computer science from the University of California, Los Angeles. She is a member of the National Academy of Engineering and has previously served on the National Academies Air Force Studies Board, the Committee for the Evaluation of NASA's Fundamental Aeronautics Research Program, and the Steering Committee for the Decadal Survey of Civil Aeronautics.

GEORGE T. LIGLER is the proprietor of GTL Associates, which provides systems integration/engineering and product management services related to telecommunications, computer system and hardware/software engineering, and information management to domestic and foreign clients. Since August 2018, Dr. Ligler has also been, on a half-time academic year basis, the Dean's Eminent Professor of the Practice in the University of North Carolina, Chapel Hill/North Carolina State Joint Department of Biomedical Engineering. He has worked as a subject-matter expert to support the FAA's implementation of both satellite-based navigation and Automatic Dependent Surveillance-Broadcast (ADS-B) as components of the Next Generation Air Transportation System. Dr. Ligler is a member of the Radio Technical Commission for Aeronautics (RTCA) Program Management Committee and the Plenary leadership group for the Industry-FAA Equip 2020 initiative related to ADS-B out equipage. He is co-chair of RTCA Special Committee-159 (Navigation Equipment Using the Global Navigation Satellite System) and a former founding co-chair of RTCA Special Committee-228 (Minimum Operational Performance Standards for Unmanned Aircraft Systems). Dr. Ligler has also been active in RTCA Special Committee-186 (Automatic Dependent Surveillance—Broadcast) since its inception in 1995. Dr. Ligler was awarded the 2006 RTCA Achievement Award, RTCA's highest award, for his contributions to ADS-B and satellite-based navigation system initiatives. He is also a co-recipient of the 2017 RTCA Achievement Award for his contributions to the development of standards for unmanned aircraft systems. Dr. Ligler holds a D.Phil. in mathematics and computation from Oxford University, with his studies supported by a Rhodes scholarship. He has previously served on the National Academies Committee on Assessing the Risks of Unmanned Aircraft Systems (UAS) Integration.

LOURDES Q. MAURICE has served on the advisory board of Boom, a start-up company working on a supersonic passenger commercial airliner, since 2017. She is also the owner of a consultancy, DLM Global Strategies, LLC, focused on aerospace, environmental issues, and international relations. Dr. Maurice was selected as executive director of the Office of Environment and Energy in 2011 and served in that post until March 2017. In this capacity, she was responsible for developing, recommending, and coordinating national and international standards, policy and guidance, research and studies, and analytical capabilities on aviation environmental and energy matters. In addition, she represented the United States in the International Civil Aviation Organization Committee on Aviation Environmental Protection. Dr. Maurice oversaw efforts to establish regulations and standards, provide guidance and technical assistance for FAA compliance with applicable federal environmental and energy statutes and regulations, and develop analytical tools and metrics to assess aviation environmental impacts. She also oversaw policy, applied science, and technical research programs to address aviation's environmental and energy issues. Dr. Maurice joined the FAA as chief scientific and technical advisor for environment in 2002. In that capacity, she served as the agency's technical expert for basic and exploratory research, advanced technology development focused on aircraft environmental impacts and its application to noise and emissions certification and policy, and the application of alternative fuels to mitigate environmental impacts. Dr. Maurice also founded, managed, and provided agency technical leadership for the Partnership for Air Transportation Noise and Emissions Reduction Center of Excellence. Prior to joining the FAA, she served as the Air Force Deputy, Basic Research Sciences and Propulsion Science and Technology, in the office of the Deputy Associate Secretary of the Air Force for Science and Technology. Dr. Maurice also worked at the Air Force Research Laboratory's Propulsion and Power Directorate from 1983 to 1999 planning and executing basic, exploratory, and advanced development propulsion science and technology programs, focusing on state-of-the-art aviation fuels and propulsion systems. Her areas of expertise include pollutant formation chemistry, combustion kinetics, hypersonic propulsion, and aviation fuels. Dr. Maurice received her B.Sc. in chemical engineering and M.Sc. in aerospace engineering from the University of Dayton and her Ph.D. in mechanical engineering from the University of London's Imperial College at London, United Kingdom. She is also a distinguished graduate of National Defense University's Industrial College of the Armed Forces, where she earned a M.Sc. in national resource strategy. Dr. Maurice has served as a lead author for the U.N. Intergovernmental Panel on Climate Change (IPCC). She was recognized as a contributor to the Nobel Peace Prize awarded to the IPCC in 2007. She is an associate editor for AIAA *Journal of Propulsion and Power* and serves on the editorial board of the *International Journal of Aeroacustics*. She has authored more than 100 publications and is a 2003 fellow of AIAA. For the National Academies, she has served on the Aeronautics Research and Technology Roundtable, the Committee on Air Force/Department of Defense Aerospace Propulsion, and the Committee for Review of NASA's Revolutionize Aviation Program.

PAUL E. McDUFFEE is business development and strategy executive at the Boeing Company. He is responsible for supporting the company's development of autonomous vehicles and operations in urban air mobility. Prior to joining Boeing, Mr. McDuffee was Insitu, Inc., vice president of government relations and was responsible for regulation shaping and development of Insitu's future in civilian and commercial use of unmanned aircraft. He continues in this role, supporting the Boeing team in FAA in matters relating to regulation for UAS operations and as advocate for UAS national airspace integration. Mr. McDuffee's involvement in UAS regulatory development is extensive. Prior to joining Insitu, he transitioned from a 30-year career in academia as a full professor and vice president of Aviation Training at Embry Riddle Aeronautical University. Mr. McDuffee joined Insitu as vice president of Flight Operations and Training before moving on to his current role. He currently serves on the Association for Unmanned Vehicle Systems International board of directors. Mr. McDuffee was a charter member of the FAA Small Unmanned Aircraft System Aviation Rulemaking Committee and former member of the FAA UAS Aviation Rulemaking Committee. He was past working group chair on the ASTM F-38 Committee, developing industry consensus standards for small UAS. Mr. McDuffee has served as co-chair of RTCA Special Committee 228 chartered by FAA to establish performance standards for UAS command and control and detect and avoid solutions. He is a recipient of the RTCA 2017 Achievement Award and received three Outstanding Leader Awards from RTCA. He was a member of the FAA/RTCA Drone Advisory Committee Subcommittee and a member of the FAA Unmanned Aircraft Safety Team Steering Committee. Mr. McDuffee is an active pilot and aircraft owner holding Airline Transport Pilot and Flight Instructor Certificates, with jet-type ratings, has logged more than 9,000 flight hours, and holds both a B.S. and M.S. from Embry-Riddle Aeronautical University. He has served on the National Academies Committee on Assessing the Risks of Unmanned Aircraft Systems (UAS) Integration.

VINEET MEHTA is vice president of engineering at AIRXOS (a GE venture) and is a member of the company's founding team. Dr. Mehta is responsible for spearheading architecture, design, development, and delivery of multiple mobile device and cloud-based software products for UAS operations, logistics, and traffic management. He is responsible for management and fiscal oversight of an engineering organization with more than 50 software engineers. Dr. Mehta was previously a group leader and principal investigator at MITRE Corporation, where he focused on various aspects of computer and network security, and was also the chief engineer at the U.S. Air Force Space and Missile Command. He received his Ph.D. from the University of Massachusetts, Lowell, in electrical engineering.

CONSTANTINE SAMARAS is an associate professor at Carnegie Mellon University in the Department of Civil and Environmental Engineering. Dr. Samaras's research spans energy, vehicle automation, technoeconomic assessment, and defense analysis, and he directs the Center for Engineering and Resilience for Climate Adaptation. He has published studies examining electric and autonomous ground and air vehicles, is a fellow in Carnegie Mellon's Scott Institute for Energy Innovation, and is an affiliated faculty member in the Traffic21 Research Center. Dr. Samaras is also an adjunct senior researcher at the RAND Corporation. From 2009 to 2014, he was a researcher at the RAND Corporation, where he led research on strategic basing of major weapons systems, defense installation analysis, and energy technology assessment. He is currently an FAA Certified Drone Pilot. Dr. Samaras received his Ph.D. in civil and environmental engineering and engineering and public policy from Carnegie Mellon University. He has previously served on the National Academies Review of the U.S. DRIVE Research Program, Phase 4 Committee.

PETER SHANNON is founder and managing director at Radius Capital. Mr. Shannon is an investor focusing on advanced aerial mobility and its application toward positive impact for transportation across the economy. He is active in the aviation community around issues critical to enabling high-scale adoption of aerial mobility systems, has published a series of articles on advanced aerial mobility, and is involved with programs attached to NASA, FAA, and private industry. Mr. Shannon holds two patents, including on vertiport network management. He also serves as an advisor or mentor for the Community Air Mobility Initiative, the Boeing GoFly prize, and the AeroInnovate startup accelerator. Earlier, Mr. Shannon was at Firelake Capital and Atlas Venture, investing in transportation and sustainability technologies. He started flying when he was 19 and actively maintains a Private Pilot Certificate with Instrument Rating. He holds an M.B.A. with high honors from the University of Chicago, Booth, and a B.S. with distinction in systems engineering from the University of Virginia. Mr. Shannon has served on the National Academies NASA Aeronautics Research and Technology Roundtable.

STAFF

DWAYNE A. DAY, *Study Director*, a senior program officer for ASEB, has a Ph.D. in political science from the George Washington University. Dr. Day joined the National Academies as a program officer for the Space Studies Board (SSB). He served as an investigator for the Columbia Accident Investigation Board in 2003, was on the staff of the Congressional Budget Office, and worked for the Space Policy Institute at the George Washington University. He has also performed consulting for the Science and Technology Policy Institute of the Institute for Defense Analyses and for the U.S. Air Force. He is the author of *Lightning Rod: A History of the Air Force Chief Scientist* and editor of several books, including a history of the CORONA reconnaissance satellite program. He has held Guggenheim and Verville fellowships at the National Air and Space Museum and was an associate editor of the German spaceflight magazine *Raumfahrt Concrete*, in addition to writing for such publications as *Novosti Kosmonavtiki* (Russia), *Spaceflight*, *Space Chronicle* (United Kingdom), and the *Washington Post*. He has served as study director for more than a dozen National Academies' reports, including *3-D Printing in Space* (2013), *NASA's Strategic Direction and the Need for a National Consensus* (2012), *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011), *Preparing for the High Frontier—The Role and Training of NASA Astronauts in the Post-Space Shuttle Era* (2011), *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies* (2010), *Grading NASA's Solar System Exploration Program: A Midterm Review* (2008), and *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008).

COLLEEN HARTMAN is the director of the ASEB and the SSB. Dr. Hartman has served in various senior positions, including acting associate administrator, deputy director of technology and director of solar system exploration at NASA's Science Mission Directorate, and deputy assistant administrator at the National Oceanic and Atmospheric Administration. Dr. Hartman was instrumental in developing innovative approaches to powering space probes destined for the farthest reaches of the solar system, including in-space propulsion and nuclear power and propulsion. She also gained administration and congressional approval for an entirely new class of competitively selected missions called "New Frontiers," to explore the planets, asteroids, and comets in the solar system. Dr. Hartman has built and launched balloon and spacecraft payloads, worked on robotic vision, and served as program manager for dozens of space missions, including the Cosmic Background Explorer (COBE). Data from the COBE spacecraft gained two NASA-sponsored scientists the 2006 Nobel Prize in Physics. Dr. Hartman earned a B.S. in zoology from Pomona College in Claremont, California, an M.P.A. from the University of Southern California, and a Ph.D. in physics from the Catholic University of America. She started her career as a Presidential Management Intern under Ronald Reagan. Her numerous awards include the Claire Booth Luce Fellowship in Science and Engineering, the NASA Outstanding Performance Award, and multiple Presidential Rank Awards, one of the highest awards bestowed by the President of the United States to senior executives.

DANIEL NAGASAWA is an associate program officer with the SSB. Before joining the SSB, he was a graduate research assistant specializing in stellar astrophysics, measuring the abundance of elements in the atmospheres of very old, metal-poor stars. Dr. Nagasawa began his research career as an undergraduate research assistant for the Cryogenic Dark Matter Search. When he began graduate school, he transitioned to designing and evaluating astronomical instrumentation, specifically ground-based spectrographs. He went on to specialize in high-resolution stellar spectroscopy and applied these techniques on stars in ultra-faint dwarf satellite galaxies of the Milky Way to study the chemical history of the Galaxy as part of the Dark Energy Survey (DES). He also developed skills in education and public outreach by teaching an observational astronomy course and writing for an outreach initiative for DES. Dr. Nagasawa earned his Ph.D. in astronomy and his M.S in physics at Texas A&M University; he earned his B.S. in physics with a concentration in astrophysics from Stanford University.

GAYBRIELLE HOLBERT is a program assistant with the Space Studies Board. Prior to joining the National Academies, she was a communication specialist for a nonprofit organization that helped inner-city youth by providing after-school programs and resources to engage their needs. Prior to that, she was the social media consultant for the Development Corporation of Columbia Heights and a production assistant for a startup multimedia production company. She holds a B.A. in mass media communications from the University of the District of Columbia.

C

Speakers to the Committee

Rex Alexander, Five-Alpha LLC
Eric Allison, Uber Elevate
Greg Bowles, Joby
Steve Bradford, Federal Aviation Administration
Carl Burlson, Federal Aviation Administration
Carey Cannon, Bell
Pamela Cohn, Ascension Global
Lisa Ellman, Commercial Drone Alliance
Kevin Fall, Roland Computing Services
James Grimsley, Choctaw Nation
Rahul Gupta, Deloitte
Davis Hackenberg, National Aeronautics and Space Administration
Jonathan Hartman, Lockheed Martin
Steve Jacobson, Autonodyne
Logan Jones, The Boeing Company
Parimal Kopardekar, National Aeronautics and Space Administration
Brock Lascara, MITRE
Ben Marcus, AirMap
Travis Mason, Airbus
Houston Mills, United Parcel Service
Colleen Reiche, Booz Allen Hamilton
Peter Shannon, Levitate Capital
Ed Waggoner, National Aeronautics and Space Administration
Mike Whitaker

D

Acronyms

2D	two-dimensional
3D	three-dimensional
ATC	air traffic control
ATM	air traffic management
DAA	detect and avoid
DoD	Department of Defense
eVTOL	electric vertical takeoff and landing
FAA	Federal Aviation Administration
NASA	National Aeronautics and Space Administration
OEM	original equipment manufacturers
UAM	urban air mobility
UAS	unmanned aircraft system(s)
UPS	United Parcel Service
UTM	Unmanned Aircraft System Traffic Management