



NASA AERONAUTICS

Strategic Implementation Plan 2023

A LETTER TO THE READER

The NASA Aeronautics Research Mission Directorate (ARMD) first rolled out the three mega-drivers and six strategic thrusts that created the backbone of this Strategic Implementation Plan (SIP) ten years ago. Since then, we've made tremendous progress and are poised to achieve major accomplishments.

We have completed Air Traffic Management Technology Demonstrations that delivered trajectory management tools to the Federal Aviation Administration and enabled implementation of the NextGen Air Traffic Management System. We are getting ready to begin flights of the X-59 to determine community acceptance of overland supersonic noise. We are building up to flight demonstrations of large megawatt class electric propulsion systems. We completed demonstrations of improved capabilities to design and certify lightweight composite structures and are now developing techniques to increase the rate at which composite structures can be manufactured. We have just awarded a partnership agreement to build a full-scale demonstration of an advanced configuration subsonic transport that is more aerodynamically efficient based on a decade of increasingly advanced research heritage. We are developing novel air traffic management capability for advanced air mobility systems, building on our success in demonstrating groundbreaking Unmanned Aircraft System traffic management capabilities. We have demonstrated powerful new software validation technologies that will speed the development and ensure the safety of complex automation systems. We are developing pathfinding innovations for prognostic safety management to ensure the future safety of the aviation system. We are inspiring and developing the next generation of diverse leaders in aviation while supporting innovative solutions aligned to this SIP through our highly successful University Innovation project. And the list goes on.

Building on this success, this update to ARMD's SIP details how we intend to continue developing and demonstrating advanced technologies that enable the aviation community to provide future air travel services that are faster, safer, and more sustainable.

The three foundational tenets of our strategic plan remain the same. First, global demand for air travel will continue to grow despite the temporary slowdown from the COVID-19 pandemic. Second, the absolute need for aviation to be a leader in environmental sustainability has substantially increased – a fact reinforced by increased demand forecasts. Third, technologies that are not traditionally associated with aviation are converging at an ever-increasing pace to advance and create new possibilities in flight.

To implement this plan, our research portfolio remains organized around six strategic research thrusts. They detail our vision for future air transportation systems that are safe and sustainable, increase personal mobility, and enhance U.S. economic well-being.

Imagine subsonic transports – the backbone of today's aviation system – that are 30 percent more efficient, delivering more affordability and fewer emissions. Imagine smaller all electric aircraft that provide enhanced local and regional mobility, enhanced economic opportunity and public benefits, while increasing the flexibility and resilience of our Nation's transportation system. Imagine overcoming the many barriers to sustainable supersonic and maybe someday hypersonic flight for very long-distance mobility. NASA Aeronautics research enables us to not only imagine, but to realize this vision. In turn, the research is made possible by taking full advantage of our Nation's diversity, vast talent, and capacity to innovate. We collaborate with our many government,

industry, and academic partners in the United States and, as appropriate, abroad.

As we look forward over the next few years, at one end of the spectrum there will be iconic flight experiments that will demonstrate the viability of the vision. And on the other end of the spectrum, groundbreaking new concepts and discoveries will fuel an even bolder vision of what is possible. We look forward to taking this exciting journey with you.

Finally, we remind you this Strategic Implementation Plan is a living document, open to new ideas and poised to respond to emerging trends. We invite and welcome your input.

On behalf of everyone here at NASA Aeronautics, thank you for your interest and support.

A handwritten signature in black ink, appearing to read 'Bob Pearce', with a long horizontal flourish extending to the right.

Mr. Robert Pearce
Associate Administrator
NASA Aeronautics Research Mission
Directorate



*Bob Pearce, Associate Administrator for the Aeronautics
Research Mission Directorate*
Credit: NASA / Bill Ingalls



Under a Funded Space Act Agreement announced in January 2023, NASA is working with The Boeing Company to develop and flight-test a full-scale Transonic Truss-Braced Wing aircraft as part of the Sustainable Flight Demonstrator project. The concept, illustrated here, involves an aircraft with extra-long, thin wings stabilized by diagonal struts. This design results in an aircraft that is much more fuel efficient than a traditional airliner due to a shape that would create less drag – resulting in its burning less fuel.

Credit: NASA

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Sustainable aviation using net-zero carbon emissions technologies and achieving fully zero harmful emissions in the long term is one of the major themes.

EXECUTIVE SUMMARY

This Strategic Implementation Plan (SIP) provides the NASA Aeronautics Research Mission Directorate (ARMD) vision for the next 25 years and beyond. It encompasses investigating a broad range of technologies to meet future needs of the aviation community, the nation, and the world for safe, efficient, adaptable, and environmentally sustainable air transportation. It is updated biennially. In this edition, sustainable aviation using technologies that support a net-zero carbon emissions aviation system and achieving fully zero harmful emissions in the long term is one of the major themes. More generally, this update to the 2019 edition reflects changes in the world affecting the aviation community.

Envisioning the long-term outcomes for aeronautics research provides the basis for new concepts leading to industry innovation and societal benefits. These include new options for air travel that are cleaner, faster, and safer. This future prompts new challenges for the aviation community. These include achieving continued growth that meets increasing global demand, safely integrating Unmanned Aircraft Systems and other innovative vehicle concepts of applications, and proactively adapting to sometimes rapidly changing conditions. An overall key objective is to solve these challenges in ways that minimize adverse impacts on the environment, with the goal of aviation achieving net-zero carbon emissions by 2050. The sustainable aviation fuel grand challenge of 3 billion gallons a year by 2030 and 35 billion gallons a year by 2050 is one of the key enabling activities toward this goal.

As in previous editions of the SIP, ARMD identified three major global trends, known as Mega-Drivers, that inform the ARMD research portfolio. For this update, ARMD performed an extensive survey to capture the evolution of previously identified trends and the emergence of new trends. Despite the impacts of the COVID-19 pandemic on the aviation community, these three major world trends remain relevant:



Mega-Driver 1 – Global Growth in Demand for Ever Faster Mobility: Reflects rapid growth in measures of global demand for mobility and new modes of air transportation.



Mega-Driver 2 – Presents innovation opportunities to solve the unique challenges associated with developing balanced options to achieve sustainability and affordability while maintaining environmentally friendly energy use.



Mega-Driver 3 – Technology Convergence: Captures the convergence of developments across industries and technologies such as materials, manufacturing, energy, information and communication, which must come together to transform aeronautical capabilities and air transportation.



NASA's X-59 aircraft is parked in stall five near the runway at Lockheed Martin Skunk Works in Palmdale, California, on June 19, 2023. This is where the X-59 will be housed during ground and initial flight tests.

Credit: Lockheed Martin

In response to the Mega-Drivers, as well as solicited feedback from the aviation community, NASA's ARMD organizes its research portfolio around six Strategic Thrusts. The six Strategic Thrusts, and the future state they would yield when the aviation community applies our research and technology developments into their operations, include:



1. Safe, Efficient Growth in Global Operations – Achieve safe, scalable, routine high tempo airspace access for all users.



2. Innovation in Commercial High-Speed Aircraft – Achieve practical, affordable commercial high-speed air transport.



3. Ultra-Efficient Subsonic Transport – Realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy.



4. Safe, Quiet, and Affordable Vertical Lift Air Vehicles – Realize extensive use of vertical lift vehicles for transportation and services including new missions and markets.



5. In-Time System-Wide Safety Assurance – Predict, detect, and mitigate emerging safety risks throughout aviation systems and operations.



6. Assured Autonomy for Aviation Transformation – Safely implement autonomy in aviation applications.

Taken together, the six Strategic Thrusts represent a future of aviation that is safer, cleaner, sustainable, more efficient and accessible, and provides more versatile mobility options than today.

ARMD focuses on high-risk, high-payoff research investments. Major technology areas of emphasis include airspace and safety technologies, ultra-efficient alternative subsonic airframe and propulsion systems including electrification and potential use of non-carbon-based fuels, supersonic flight over land, automation and autonomy, fostering new aviation applications in Advanced Air Mobility (AAM), and fundamental research involving high-speed flight well beyond the speed of sound. Collectively, these efforts, other technologies, and a focus on technology convergence will develop transformative solutions toward the goal of a safe, efficient, adaptable, and environmentally sustainable global aviation system.

The foundation on which this research is built is NASA's dedicated and diverse multidisciplinary teams of aeronautical innovators. They are equipped with world class research facilities and capabilities that include wind tunnels, computational tools, and flight test hardware.

Aviation is a critically important industry for the United States and has a vital role as an economic engine.

INTRODUCTION

During 2015, ARMD published the initial edition of the SIP, setting forth a vision for aeronautical research aimed at the next 25 years and beyond based on NASA's synthesis of the aviation community's view of the future of civil aviation. It is updated biennially to ensure our strategy benefits from, and is reflective of, rapid advances in technology as well as new national priorities.

This edition reflects work that has been implemented to achieve the ARMD vision and includes refined language describing research taking place within each Strategic Thrust. A notable theme present throughout the document relates to sustainable aviation and a global aviation industry commitment to achieving net-zero carbon gas emissions by 2050 – a goal that will require innovations in aircraft and engine technology, operational efficiency, and sustainable aviation fuel. While most scenarios require the use of high-integrity offsets for residual aviation-related emissions, NASA aims to minimize or eliminate the need for high-integrity emission offsets.

OVERVIEW

Aviation is a critically important industry for the United States and has a vital role as an economic engine. ARMD's mission is to serve the future needs of U.S. commercial aviation by conducting research and technology development, in concert with our industry and government partners, to find solutions to the difficult challenges of future aviation. While those specific research challenges have changed considerably since the early days of aviation, NASA's aeronautical investigations remain as important as ever to benefit the public and maintain U.S. leadership in all things related to flight.

The Domestic and Global Roles of Air Transportation

As a primary mechanism for physically connecting countries across the world, air transportation is an integral part of today's U.S. and global economies. Aviation enables U.S. enterprises to operate on a global scale, providing safe, high-speed transport of people and goods. More than 21.3 million tons of freight were moved by air in the United States in 2019,¹ as well as 926 million passengers.²

As evidenced by the ever-increasing amount of goods transported by aircraft – an expansion influenced by e-commerce and the promise of quick delivery – aviation has become an even more critical element of today's complex and time-sensitive supply chain network. Safe and efficient aviation operations are paramount to ensure that balance in the supply chain is maintained across industries.

In 2019, aviation accounted for \$1.8 trillion of U.S. economic activity and generated a positive trade balance of \$78 billion. The aviation industry also supported nearly 11 million direct and indirect jobs, including more than one million

1 Bureau of Transportation Statistics, <https://www.transtats.bts.gov/freight.asp?20=D&qv52ynB=qn6nF>, Accessed Sept. 2, 2022.

2 Bureau of Transportation Statistics, https://www.transtats.bts.gov/Data_Elements.aspx?Data=2, Accessed Sept. 2, 2022.

high-quality manufacturing jobs. In short, the U.S. aviation industry is critical to both economic and societal well-being.³

The COVID-19 pandemic dramatically impacted the aviation sector during 2020, resulting in drastic reductions in passenger air travel. This, in turn, reduced demand for both new aircraft and engines. The latest transportation statistics indicate these trends are rapidly reversing as recovery in business and family travel markets strengthens.

Global economic growth and urbanization are expected to drive increases in demand for air travel, especially in the Asia-Pacific region and other high-growth, developing areas. The International Air Transport Association forecasts annual demand to reach 10 billion air passengers by 2050.⁴ It follows that the demand for new aircraft and air transportation services will grow to keep pace. This expectation represents a substantial opportunity for U.S. economic growth through leading-edge products and services, as well as providing a variety of benefits to society on a global scale.

The Need for Sustainable Aviation

With the projected steady growth in demand for aviation, the corresponding release of emissions also will increase. It should be noted that older (and less efficient) passenger aircraft are being converted into freighters to meet e-commerce demands, which exacerbate the emissions challenge. Every kilogram of jet fuel creates approximately 3 kilograms of carbon dioxide (CO₂).⁵ So, aircraft efficiency is fundamental to sustainability. In 2018, aviation contributed approximately 2.5% of global CO₂ emissions. These relative contributions are expected to increase as global CO₂ emissions are reduced in other industries.

In 2021, the United States released the Aviation Climate Action Plan, which predicts nearly doubling of CO₂ emissions per year from the U.S. aviation sector by 2050 if not mitigated.⁶ This plan provides a whole-of-government approach for the aviation sector to achieve ambitious climate goals by implementing a suite of measures to drive innovation across the entire aviation ecosystem. This includes airlines, airports, energy producers and suppliers, manufacturers, and various levels of government.

The U.S. aviation climate goal is to achieve life-cycle net-zero greenhouse gas emissions from the U.S. aviation sector by 2050. This includes employing means where CO₂ still can be produced if other mitigating measures – such as high-integrity offsets or measurably reduced levels of contrail formation – exist. This could include carbon sequestration, which is the process of capturing and storing atmospheric CO₂ possibly through geological or biological methods.

3 The Economic Impact of Civil Aviation on the U.S. Economy, https://www.faa.gov/about/plans_reports/media/2020_jan_economic_impact_report.pdf, Jan. 2020.

4 Net-Zero Carbon Emissions by 2050, <https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/>, Oct. 4, 2021.

5 IATA Carbon Offset Program Frequently Asked Questions, https://www.iata.org/contentassets/922ebc-4cbcd24c4d9fd55933e7070947/icop_faq_general-for-airline-participants.pdf, April 19, 2022.

6 United States 2021 Aviation Climate Action Plan, https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf, 2021.

Emissions from aircraft engines include CO₂, water vapor with very small amounts of nitrogen oxides, sulfur oxides, and non-volatile compounds. The harmful impact from non-CO₂ emissions on the climate and local air quality have been studied for several decades and can last from several hours (e.g., contrails) to decades. Therefore, research on fully zero harmful emissions and contrail formation also is critical for eliminating aviation's impact on climate.

NASA is committed to supporting this ambitious sustainability and climate goal through a time-phased and mission-dependent technology development approach. In addition, NASA is actively engaged in identifying, developing, and demonstrating high-risk, high-payoff technologies that accelerate us toward net-zero emissions and beyond.

The Role of Research in the U.S. Aviation Industry

Today, NASA is making significant contributions to fundamental understanding in areas critical to the future of aviation, including technologies that will facilitate implementation of system-wide safety assurance, use of alternate energy sources for power and propulsion, vehicle efficiency improvements, and reduction of noise and harmful emissions. The future promises new sustainable advances in aviation.

Long-term aeronautics research provides the basis for new concepts that ultimately lead to industry innovation and value to society. For example, the potential for AAM to serve myriad needs – from battling wildfires, to retail distribution, to delivering urgently needed medical supplies at remote locations, to more rapidly moving first responders to accident sites – is becoming reality. ARMD focuses on research and technology development outside the economic and risk criteria that govern commercial investments, with emphasis on technologies to achieve public benefits such as safety assurance and environmental protection. NASA's many partners throughout the aviation community view ARMD as the stewards of the nation's aeronautics research enterprise.

NASA AERONAUTICS RESEARCH YESTERDAY AND TODAY

The year 2015 marked the 100th anniversary of the founding of NASA's predecessor, the National Advisory Committee for Aeronautics (NACA). The NACA was established on March 3, 1915, by a rider to the Naval Appropriations Act. The legislation chartered the new organization to "supervise and direct the scientific study of the problems of flight, with a view to their practical solution."

Throughout the last century, aeronautical research has involved a combination of empirical knowledge gained from ground and flight testing, development of theory and analytic methods, and confirmation by physical demonstration. This research has encompassed an ever-broadening array of technologies, enabling increased performance, enhanced safety, greater efficiency, and reduction of adverse environmental impact.

Initial research by the NACA focused on the physics of flight, with work involving wind tunnel tests and flight tests of both models and full-scale aircraft. This work, especially during and after World War II, established the United States as the global leader in aeronautics.

The 1958 Space Act established NASA as the successor to the NACA, marking expansion of its research to flight beyond Earth's atmosphere. As the human spaceflight program advanced and gained worldwide attention, NASA's aeronautical innovators continued their work. The 1960s and 1970s witnessed development of the widely used NASA structural analysis tools and initial development and application of computational fluid dynamics. During the 1980s, NASA's aviation research portfolio grew to include several important safety and performance enhancements that contributed to a transformation of commercial air transportation. Accomplishments since 1990 demonstrated not only further expansion of NASA's aeronautical research, but also a shift to treating aviation as a complex system of systems that integrates a wide variety of technologies to provide safe, efficient, and environmentally sustainable air transportation.

With the purpose of proactively transitioning its results to the aviation community, NASA consistently undertakes research and development efforts that are outside the scale, risk, and return-on-investment criteria that often govern commercial investments. NASA's aeronautical research has transformed aviation for the benefit of the national economy, national defense, the traveling public, and the transportation industry – all while fostering efforts to minimize environmental impacts. As an example, Figure 1 illustrates major features of modern commercial aviation made possible by NASA aeronautical research.

This brief history of NASA aeronautics underscores the continuing need to expand and adjust the scope of ARMD's research to address the public good, meet emerging needs of the aviation community, and exploit new technologies not previously associated with aviation. ARMD's strategy continues to focus on making efficient investments to enable the transformation of aviation to serve future needs, enable demonstrable benefits, and leverage technology advances both within and outside of traditional aviation disciplines.

In fact, since the first SIP was published in 2015, near-term outcomes presented in that edition have been realized. For example, these include multiple traffic management technologies transferred to the Federal Aviation Administration (FAA) to enable the Next Generation Air Transportation System (NextGen),⁷ as well as advances in autonomy of large Unmanned Aircraft Systems.⁸ Studies on the use of sustainable aviation fuels confirmed some of the challenges related to propulsion system plumbing when using unblended fuels, as well as demonstrating environmental benefits of blended fuels including reduced particulate emissions that lead to contrail formation.⁹ The X-59 has been designed and built, and will soon take flight on its mission to help enable commercial supersonic air travel over land. Tools needed to develop electric vertical takeoff and landing technologies have been demonstrated.¹⁰ And every aspect of developing AAM – vehicles, infrastructure, operations – has seen progress.

7 NASA Transfers Air Traffic Management Tool Updates to FAA, <https://www.nasa.gov/press-release/nasa-transfers-air-traffic-management-tool-updates-to-faa>, Sept. 28, 2021.

8 NASA Flies Large Unmanned Aircraft in Public Airspace Without Chase Plane for First Time, <https://www.nasa.gov/press-release/nasa-flies-large-unmanned-aircraft-in-public-airspace-without-chase-plane-for-first>, June 12, 2018.

9 NASA-DLR Study Finds Sustainable Aviation Fuel Can Reduce Contrails, <https://www.nasa.gov/press-release/nasa-dlr-study-finds-sustainable-aviation-fuel-can-reduce-contrails>, June 17, 2021.

10 Revolutionary Vertical Lift Technology project web page, <https://www.nasa.gov/aeroresearch/programs/aavp/rvlt>.

NASA AERONAUTICS RESEARCH ONBOARD DECADES OF CONTRIBUTIONS TO COMMERCIAL AVIATION

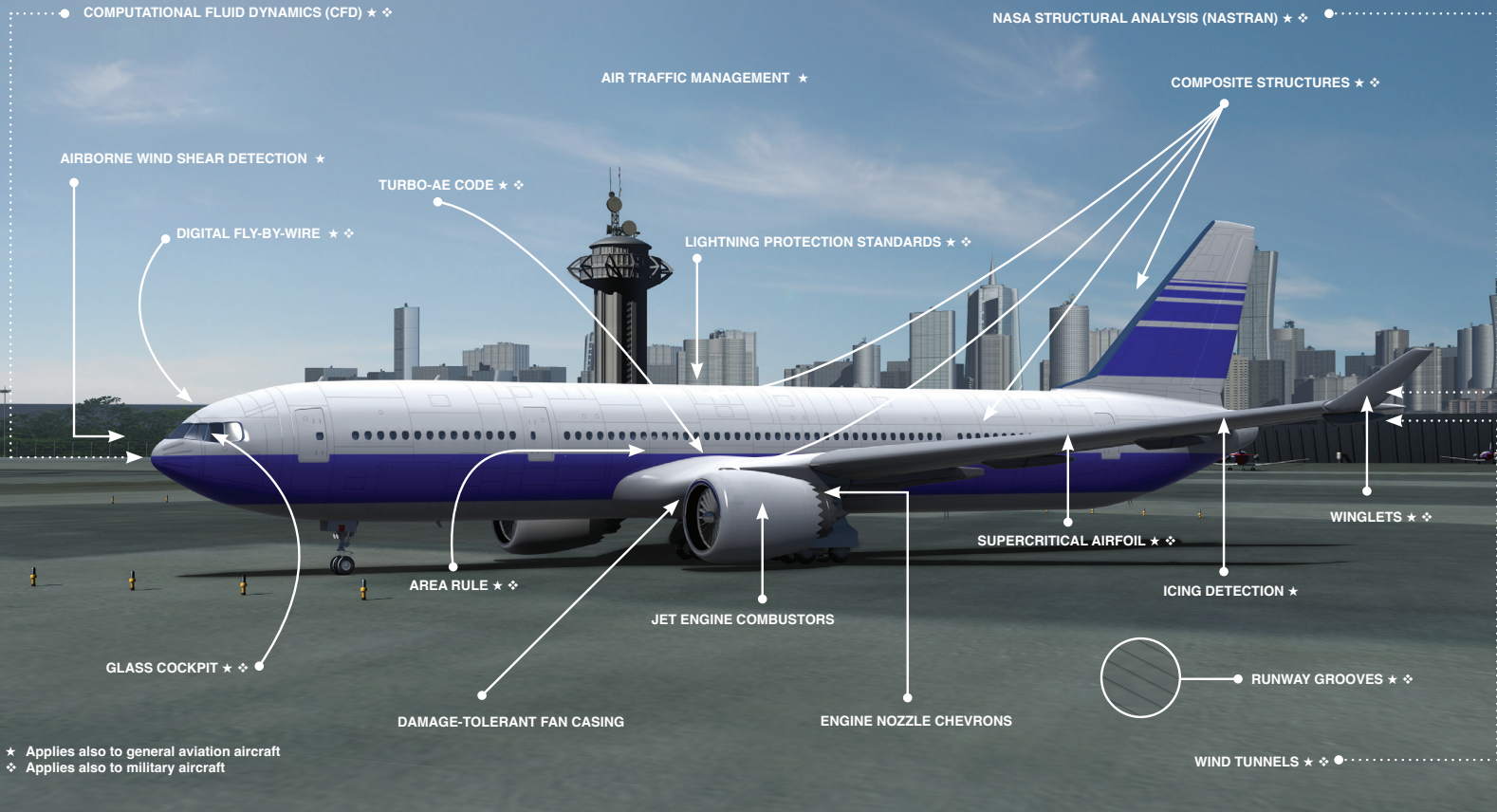


Figure 1. Applications of NASA Research Results in a Modern Commercial Aircraft



NASA's Glenn Research Center in Cleveland during 2022 took delivery of a Pilatus PC-12 aircraft, which will take on a key role in the agency's investigation of how to manage the emerging advanced air mobility ecosystem. Initially, it will be used to evaluate commercial communications technologies that will allow highly automated transportation systems to operate and move passengers or cargo at lower altitudes within urban and suburban areas.

Credit: NASA

NASA AERONAUTICS STRATEGY

While past NASA aeronautics research has provided the U.S. aviation industry with transformative technologies, current global trends – both economic and climatological – demand yet another shift in focus beyond traditional research areas. Moreover, in defining NASA's approach to meeting future aviation needs, the overall 2022 NASA Strategic Plan calls on NASA's ARMD to “drive efficient and sustainable aviation,” (strategic objective 3.2) by leading aviation innovation to enable safe and sustainable air transportation through revolutionary vehicle advances and efficient flight operations.¹¹ ARMD is answering that call with the updates embodied in this SIP.

Figure 2 represents our vision for the 21st century: Our high-risk, high-payoff research enabling safer, more efficient, and sustainable air travel with unprecedented mobility.

NASA Aeronautics Vision for the 21st Century



Figure 2. NASA Aeronautics Vision

¹¹ NASA Strategic Plan 2022, https://www.nasa.gov/sites/default/files/atoms/files/fy_22_strategic_plan.pdf, March 28, 2022.

ARMD'S STRATEGIC PLANNING PROCESS

The SIP provides a basis to guide research across a wide range of technology initiatives, helping to maintain the nation's aeronautical leadership and supporting U.S. industry's ability to meet the needs of global aviation markets while assuring global sustainability goals.

ARMD's vision, therefore, considers the wider roles of aviation and aviation research organizations on a global scale. Partnerships with other government agencies, industry, academia, and foreign aeronautics agencies leverage ARMD's investments through joint efforts that complement NASA's internal capabilities, provide access to a wide range of technologies, and accelerate technology maturation toward providing in-service capabilities and benefits.

ARMD's research strategy operates within this collaborative global research environment, building on current leadership to enable revolutionary technological advances. ARMD also employs a strategic portfolio management process to ensure that potential future opportunities are regularly assessed for possible incorporation into the ARMD research portfolio.

Table 1 depicts the hierarchy of elements guiding ARMD's aeronautics research planning.

NASA'S AERONAUTICAL RESEARCH ROLE

Address Research Needs Within Three Overarching Trends Affecting Future Aviation



Mega-Driver 1: Global Growth in Demand for Ever Faster Mobility



Mega-Driver 2: Sustainability, Affordability, and Energy Use



Mega-Driver 3: Technology Convergence

ARMD'S AERONAUTICAL RESEARCH TAXONOMY

Strategic Thrusts



1. Safe, Efficient Growth in Global Operations



2. Innovation in Commercial High-Speed Aircraft



3. Ultra-Efficient Subsonic Transport



4. Safe, Quiet, and Affordable Vertical Lift Air Vehicles



5. In-Time System-Wide Safety Assurance



6. Assured Autonomy for Aviation Transformation

Outcomes

Outcomes are defined in terms of the envisioned future state.

Research Themes

Research themes are long-term research areas that enable the outcomes.

Technical Challenges

Technical challenges are specific, measurable research activities.

Table 1. ARMD's Aeronautics Research Planning Framework

The Mega-Drivers are three overarching global trends that shape, in large part, requirements of aeronautical research during the coming years. ARMD funds research that is both within the capabilities of NASA aeronautics expertise and resources, and beyond the willingness of industry to invest in high-risk, high-payoff research.

The Strategic Thrusts represent ARMD's response to the Mega-Drivers and input from the aviation community. They are mutually supportive and evolve in response to changes in Mega-Drivers and community needs. In this update, the Strategic Thrusts represent a future of aviation that is safer, sustainable, and more efficient, all while providing unprecedented advances in mobility options for emerging markets. This future may be realized when NASA aeronautics research enables new technical capabilities, and the aviation community implements them into operations.

Outcomes associated with each Strategic Thrust signify the in-service capabilities and benefits envisioned for the public and stakeholders upon realizing the future of aviation. They are envisioned future states that are more than NASA alone can achieve. They are achieved through joint efforts across the aviation community, where NASA is considered a trusted, independent organization that brings organizations together. NASA aeronautics research is meant to technically enable each Outcome, but others (e.g., the FAA; the departments of Agriculture, Commerce, Defense, and Energy; the National Oceanic and Atmospheric Administration; the industrial base across the entire aviation supply chain, etc.) have key roles in achieving the Outcomes and realizing the community's view.

The Outcomes are divided across the future into near-, mid-, and far-term time periods during which research results are transitioned from concept to practice:

NEAR-TERM (2020-2035)

Outcomes generally leverage partnerships to demonstrate feasibility of potential applications. They enjoy a greater degree of confidence within the aviation community and generally involve focused technology partnerships to enable the Outcomes.

MID-TERM (2035-2045)

Outcomes are often in a transitional stage, aimed at a combination of new concepts and applications within the current system. They reflect applications of emerging technologies, initially within the paradigm of the existing aviation system, but often leading to transformative innovations responsive to future needs.

FAR-TERM (BEYOND 2045)

Outcomes are more exploratory in nature, focusing on concept exploration and technology research. For these Outcomes, ARMD takes a greater role in performing and sponsoring concept exploration and fundamental research.

Research Themes represent ARMD's long-term research focus in particular technology areas required by the Outcome.

The Technical Challenges serve as the basis for planning research activities and measuring performance. In some cases, the output (technical solutions) from solving

the Technical Challenges can be applicable to multiple Strategic Thrusts, which increases the effectiveness of NASA ARMD's investment response.

MEGA-DRIVERS

The three Mega-Drivers that emerged from the global trend analysis (global growth in demand for ever faster mobility; sustainability, affordability, and energy use; and technology convergence) structure ARMD's strategic response and shape major aeronautics research. ARMD has established six Strategic Thrusts based on an analysis of how these global trends will potentially determine the future of aviation. It is noteworthy to mention that as of this update, there is no indication that the COVID-19 pandemic caused a shift in the mega-drivers. NASA strategy will respond if a shift is detected.

Mega-Driver 1: Global Growth in Demand for Ever Faster Mobility



During the past 50 years, the economies of both China and India have grown more than twice as fast as the U.S. economy.¹² These countries are expected to account for half of the world's middle-class population by 2050.¹³ Since the urban middle class constitutes a major air transportation market, growth in this population segment will dramatically increase the need for greater, faster, and more efficient air mobility. To support that growth in demand, high-technology aircraft powered by advanced alternative energy sources will be needed. In addition, interest in new types of missions is expected to herald introduction of new types of aircraft including ultra-efficient transports that feature hybrid-electric propulsion and/or novel airframe configurations, as well as commercial supersonic aircraft enabled to fly over land.

A century-long trend of migration into cities across the globe is generating urban growth to the extent that more than half of the world's population likely will live in urban centers by 2050. As migration leads to expansion of geographical city boundaries, the demand for ever faster inter- and intra-city travel will be met by a combination of several modes of transports. AAM is one such mode and is expected to have a key role in meeting this demand. Cities around the world are recognizing the potential of AAM and the corresponding proliferation of new types of air vehicle missions (e.g., electric vertical takeoff and landing air taxis and small drones to deliver food, consumer goods, and medical supplies, etc.). These vehicles also could extend the reach of aviation to underserved localities like rural communities or hard to reach areas. This increasing diversity of operations will lead to substantially higher air traffic than today.

While passenger volumes declined during 2020 through early 2022 due to the pandemic, air freight operations and demand grew to historic levels with a consumer shift in methods of acquisition of goods. By mid-2022, U.S. domestic passenger volumes were beginning to exceed the pre-pandemic demand, and with an

¹² The World Bank Group, "GDP growth (annual %) – United States, China, India," <https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?end=2021&locations=US-CN-IN&start=1971&view=c>, 2023.

¹³ Karen Ward and Frederic Neumann. "Consumer in 2050: The rise of the EM [Emerging Market] middle class." HSBC Global Research, October 2012.

increased rebound of international travel, the combined demand is expected to exceed pre-pandemic levels. This also will cause an increase in air traffic as airlines add more capacity to their fleets.

Mega-Driver 2: Sustainability, Affordability, and Energy Use



Fuel is currently a significant driver of the cost of air transportation. According to the International Air Transport Association, fuel is the only major element of air transportation cost that has grown significantly over time. For example, prices of jet fuel rose by about a factor of seven between 1990 and 2022. Fuel made up only 10 percent of total airline costs in 1995, but it increased to about 17 percent pre-pandemic in 2019. Despite recent volatility in fuel prices, evidenced by a more than 50% reduction in the cost of jet fuel since the 2012-2013 peak, energy costs are projected to continue rising over the long term, affecting affordability of air transportation and sustainability of current models of operation. Scarcity of non-renewable energy sources is another factor affecting the fuel prices.

Air transportation accounts for about 2.1 percent of the world's CO₂ emissions.¹⁴ While this is a relatively small share, continued growth in air transportation and CO₂ reductions in other sectors could lead to increased contribution from aviation. The industry has ambitious goals for reducing the generation of CO₂ to enable sustainable growth and address climate change. The International Civil Aviation Organization Assembly at its 40th session in 2019 adopted a resolution to reiterate two global goals for the international aviation sector of a 2 percent annual fuel efficiency improvement through 2050 and carbon neutral growth from 2020 onwards.¹⁵ Moreover, the United States in 2021 released its Aviation Climate Action Plan that describes a whole-of-government approach and policy framework for the aviation sector to meet net-zero gas emissions by 2050 and efforts to increase scientific understanding of impact from non-CO₂ emissions.

Mega-Driver 3: Technology Convergence



Technology convergence is widely defined as the combination of two or more different technologies in a single device or product. This seemingly simple definition, however, masks the fact that systems embodying convergent technologies have often led to radical changes in affected industries and supply chains, marketing and distribution, infrastructure, and uses of the system, along with wide economic and social ramifications. ARMD seeks to leverage rapid advancements in technologies and standards across many sectors, as well as emerging operational concepts enabled by the convergence of these technologies, to develop revolutionary solutions for future aviation challenges.

Technology convergence, for example, may be seen as an enabler for AAM as new producers, users, technologies, and missions converge to capture the promise of

¹⁴ Air Transport Action Group, Facts & Figures, <https://www.atag.org/facts-figures.html>, 2022

¹⁵ International Civil Aviation Organization. Doc 10140. Assembly Resolutions in Force. https://www.icao.int/publications/Documents/10140_en.pdf, October 4, 2019.

AAM. Machine learning, artificial intelligence, and robotics could lead to on-demand aviation that would radically transform personal mobility and aviation services.

Thus, technology convergence is expected to amplify the benefits of new concepts and technologies in existing as well as emerging aviation markets. However, technology convergence brings new risks and hazards that must be understood and mitigated, such as the creation of new potential safety issues and convergence on new issues related to privacy, regulation, and airspace management. Technology convergence may also affect future demand for aviation by enabling innovations such as high-fidelity, multisensory telepresence that could reduce the demand for air travel by partially substituting for physical transportation.

COMMUNITY DIALOGUE

In addition to strategic analyses and inputs from subject matter experts and senior stakeholders, ARMD's strategic planning incorporates mechanisms for dialogue with the aviation community on a wide range of topics. To help identify important research areas and challenges of the future, ARMD frequently engages the aviation community to understand what its stakeholders believe are priority research areas. Regular discussions engage domestic and international partners and experts from industry, academia, and other government agencies. Interactions have included regular reviews of ongoing research by federal advisory committees and dialogue sessions with the National Research Council's Aeronautics Research and Technology Roundtable.

The aviation community's highest priorities for research are in safety, highly efficient aircraft, the completion of the NextGen 2025, evolution of the 2035 Info-Centric National Airspace System (NAS), automation and autonomy, and the rapidly expanding interest in the potential of AAM. Recent community focus on AAM vehicles, airspace management of these vehicles, and infrastructure challenges has increased. Facilitating advances in all of these areas will require the development of tools for more innovative virtual testing and verification and validation of complex systems. Additionally, flight research continues to be a critical element in the maturation of technology, and it can help to establish strong public-private partnerships. Serving these expressed community needs forms an integral part of ARMD's research plans.

ARMD has engaged with the National Academies of Science, Engineering, and Medicine to perform detailed studies of national focus on the ARMD Strategic Thrusts and related topics. These studies provide in-depth information that help support ARMD detailed research planning and partnership development.¹⁶ Additionally, ARMD recognizes that its research will affect, and be affected by, the work of a wide array of U.S. and international researchers. For that reason, ARMD places major emphasis on maintaining communications and collaborative relationships with the full range of researchers working in government agencies, industry, and academia. AAM Ecosystem Working Groups are an example of this kind of collaboration.

16 Links to completed studies are available at <https://www.nasa.gov/aeroresearch/national-academies-reports>.

STRATEGIC PARTNERSHIPS

Partnerships with other government agencies, industry, academia, and foreign aeronautics agencies leverage ARMD's investments through joint efforts that complement NASA's internal capabilities and provide access to a wide range of technologies and expertise. These partnerships facilitate rapid technology maturation and accelerate in-service capabilities and benefits. Integrated technology demonstrations typically include selected industry or government partners who contribute their own funding and knowledge, and/or provide in-kind contributions. These partnerships also give ARMD deep insight into the goals and needs of the aviation community, as well as providing user feedback and facilitating industry engagement early in the technology development cycle.

ARMD collaborates closely with the FAA to support that agency's decision making and to improve the performance of the NAS, as well as with the Department of Defense and other government agencies to leverage technology investments. Industry partnerships allow rapid insertion of NASA aeronautics research results into air vehicles and subsystems, as well as NAS operations, tools, and processes. Partnerships with domestic academic institutions support cutting-edge research on emerging aviation technologies and on the education of new researchers. To help address the global nature of air transportation, ARMD also forges partnerships with a wide range of international government entities, such as the International Forum for Aviation Research.

To broaden its perspective and impact, ARMD complements its formal partnerships by participating in various public forums, including conferences, industry days, working groups, and technical interchange meetings. These activities help to identify needs and areas of potential technical interest that could produce future partnership opportunities.

STRATEGIC RESPONSE

ARMD has formulated six Strategic Thrusts to organize and prioritize our response to the Mega-Drivers. They are summarized below. Detailed descriptions are presented later in this document.

Strategic Thrust 1: Safe, Efficient Growth in Global Operations



Within the United States, NextGen is the focus for a modernized air transportation system that will support anticipated growth in demand and is operationally efficient while maintaining or improving safety and other performance measures. ARMD will contribute specific research and technology to enable the realization of

NextGen and continued development beyond for the Info-Centric NAS to achieve safe, scalable, routine, high-tempo airspace access for all users. Similar ongoing international developments, such as the European Union's Single European Sky Air Traffic Management Research effort, are being globally harmonized through the International Civil Aviation Organization. ARMD also will work with the emerging AAM ecosystem, developing concepts and technologies to enable a

safe, scalable system for the growth of this new transportation sector.¹⁷ Projected growth in air travel of all types will require a sustained focus on reducing risks to maintain acceptable levels of safety; to that end, ARMD will work with the FAA, the Commercial Aviation Safety Team, and others to perform research and contribute technology that addresses current and future safety risks.

Strategic Thrust 2: Innovation in Commercial High-Speed Aircraft



Development of efficient, cost-effective, and fully sustainable commercial high-speed transports could be a game changer for transcontinental and intercontinental transportation, providing an opportunity to maintain U.S. leadership in aviation systems and generate economic and societal benefits in a globally linked world.

To achieve practical and affordable commercial high-speed air travel, ARMD will focus on advancing groundbreaking technologies that overcome barriers to reducing its environmental impact – including use of sustainable aviation fuels -- and realizing innovative economic efficiencies. Since overcoming these barriers likely will involve modifications to regulations and certification standards for high-speed flight, ARMD will conduct its research in cooperation with the FAA, International Civil Aviation Organization, and other aviation regulatory agencies.

Strategic Thrust 3: Ultra-Efficient Subsonic Transport



Significant improvements in aircraft efficiency, coupled with reductions in noise and harmful emissions, are critical to realizing the aviation community's projections for growth while achieving increasingly challenging national and international environmental sustainability goals. ARMD seeks to enable substantial efficiency

gains through vehicle and propulsion technologies. This includes innovative alternative energy-based propulsion systems through the hybrid-electrification of aircraft propulsion in the mid-term, and reduced demands on sustainable aviation fuel production and potential use of other renewable, non-drop-in energy/fuel solutions in the far-term. ARMD also is working to enable substantial reductions in time and cost to market of aircraft through advanced materials, structures, and manufacturing technologies and enhanced digitalization of the full aircraft life cycle to accelerate aircraft benefits into service. ARMD will work across government, the transport industry, and academia to develop critical technologies to enable revolutionary improvements in economics and environmental performance for subsonic transports. ARMD will actively seek opportunities to transition to alternative propulsion and energy for all categories of subsonic transports, including short-haul and regional aircraft but with an emphasis on large commercial aircraft that dominate aviation's impact on the environment.

¹⁷ Federal Aviation Administration, "Charting Aviation's Future: Operations in an Info-Centric National Airspace System," https://www.faa.gov/sites/faa.gov/files/Charting-Aviations-Future-Operations-in-ICN_0.pdf, September 2022.

Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles



The aviation community expects new and cost-effective uses of aviation including advanced vertical takeoff and landing vehicles and other novel small aircraft that could provide air travel as another transportation mode where it has not historically been practical.

Intra-city air travel could provide unprecedented availability and potentially shorter origin-to-destination travel times compared to other modes of transportation. While this capability is expected to greatly increase the demand for air service and significantly increase the number of flights, this mode of air travel will only be practical if the advanced aircraft utilized for these operations provide acceptable levels of safety while reducing their environmental footprint (noise and emissions) compared to existing vertical takeoff and landing aircraft. ARMD will work across government, industry, and academia to develop critical technologies to enable realization of extensive use of vertical lift vehicles for transportation services, including new missions and markets associated with AAM.

Strategic Thrust 5: In-Time System-Wide Safety Assurance



In-Time System-Wide Safety Assurance (ISSA) is a safety net that utilizes system-wide information to provide alerting and mitigation strategies in time to address emerging risks. Moving forward, aviation safety needs to take advantage of modern information availability and intelligent systems. New operational concepts will

change and diversify aviation and create the need for advanced safety capabilities that operate on a broad scale. ISSA will incorporate both advanced technologies and collaboration between humans and intelligent agents. ISSA must be both system-wide and distributed. The vision for ISSA is to predict, detect, and mitigate emerging safety risks throughout aviation systems and operations.

Strategic Thrust 6: Assured Autonomy for Aviation Transformation



Ever-increasing levels of automation and autonomy leveraging modern information availability are transforming aviation and the transportation of both people and goods, and this trend will continue to accelerate. ARMD will lead in the research and development of intelligent machine systems capable of operating in

complex environments, including the safe integration of larger Unmanned Aircraft Systems and smaller AAM vehicles into the NAS. A collection of complementary methods will be utilized to provide safety assurance, verification, and validation of these systems. To pave the way for increasingly autonomous airspace and vehicles, ARMD will explore human-machine teaming strategies. Advanced metrics, models, and testbeds will enable the effective evaluation of autonomous systems in both laboratory and operational settings to safely implement autonomy in aviation applications.

STRATEGY IMPLEMENTATION

NASA aeronautics research creates opportunities for industry to participate in realizing, or benefit from, the various future states of aviation described in the six Strategic Thrusts. NASA ARMD's four program offices develop the Technical Challenges and ensure that NASA Aeronautics works to enable the Outcomes developed and maintained in response to this SIP. Research activities are executed within projects hosted among four of NASA's field centers in Virginia, Ohio, and California. The projects follow NASA policies for formulating and executing NASA research and technology projects.

NASA's research activities are organized within these four programs:

- The Airspace Operations and Safety Program performs research and technology development to enable the transformation of the NAS to safely accommodate a growing number of diverse and increasingly autonomous new vehicles, operational concepts, and missions.
- The Advanced Air Vehicles Program conducts cutting-edge research that will generate innovative concepts, technologies, capabilities, and knowledge to enable revolutionary advances for a wide range of air vehicles.
- The Integrated Aviation Systems Program conducts research on promising concepts and technologies at an integrated system level, with a focus on flight research and demonstrations. The program works with others to forecast and plan for needed flight research and demonstrations in support of all Strategic Thrusts.
- The Transformative Aeronautics Concepts Program cultivates multi-disciplinary, revolutionary concepts to enable aviation transformation, harnesses convergence in aeronautics and non-aeronautics technologies, and creates new opportunities throughout aviation. The program's goal is to demonstrate initial feasibility of internally and externally originated concepts to support the discovery and development of new, transformative solutions for all Strategic Thrusts.

Major challenges to achieving the community Outcomes – and research activities designed to overcome them – are identified in the following sections detailing each Strategic Thrust. In addition, ARMD conducts crosscutting research in fundamental technologies that support multiple Strategic Thrusts. These crosscutting technologies are summarized later.

At NASA's air traffic management laboratory near the Dallas/ Ft. Worth International Airport in Texas, researchers Al Capps (seated) and Paul Borchers demonstrate Airspace Technology Demonstration 2 tools that air traffic managers successfully tested at the Charlotte Douglas International Airport in North Carolina to more efficiently direct departing traffic. Credit: NASA / Jim Banke





STRATEGIC THRUST 1: **SAFE, EFFICIENT GROWTH IN GLOBAL OPERATIONS**

The vision for Strategic Thrust 1 is to achieve safe, scalable, routine high-tempo airspace access for all users. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

COMMUNITY'S VISION

For the past 15 years, the FAA's NextGen program has been the focus for modernizing the air traffic management system to achieve much greater capacity and levels of operational efficiency while maintaining or improving safety and other performance measures. As NextGen is being implemented, the FAA continues its modernization, focusing on the digital transformation of the NAS, as described in "Charting Aviation's Future: Operations in an Info-Centric National Airspace System."¹⁸ Strategic Thrust 1 responds to the FAA 2035 Info-Centric NAS vision to build upon NextGen beyond 2025 for collaborative, distributed decision making and in-time safety management and to fully leverage the opportunities enabled by cyber-physical systems research and other emerging technologies. More efficient aircraft operations will reduce energy consumption, complementing Strategic Thrust 3 in offering options for environmentally sustainable aviation. In addition, emergent vehicles such as AAM, High Altitude Long Endurance, high-speed, and ultra-efficient transport category aircraft will make future global operations far more diverse, complex, dense, and will substantially increase traffic volume.

Throughout the 2020-2045 period and beyond, Strategic Thrust 1 also responds to specific safety hazards associated with existing or new aircraft, such as near-term needs to reduce loss-of-control accidents of commercial transports and the long-term need to maintain safety of the NAS.

¹⁸ Federal Aviation Administration, "Charting Aviation's Future: Operations in an Info-Centric National Airspace System," https://www.faa.gov/sites/faa.gov/files/Charting-Aviations-Future-Operations-in-ICN_0.pdf, September 2022.

For beyond 2045, Strategic Thrust 1 responds to NASA's 2045 Sky for All vision¹⁹, jointly developed with the FAA and industry, for highly automated and dynamically adaptable and scalable air transportation operations with automatically assured adaptive in-time safety management to meet the diversity, density, complexity, and volume of future operations.

Figure 3 shows the evolution of airspace operations and safety across the epochs between today and beyond 2045, where Info-Centric NAS is shown in Epoch 4, and Sky for All is shown in Epoch 5. The U.S. Info-Centric NAS and Sky for All are intended to ensure global competitiveness of the U.S. aviation sector against other global initiatives such as the European Commission's Single European Sky Joint Undertaking vision.

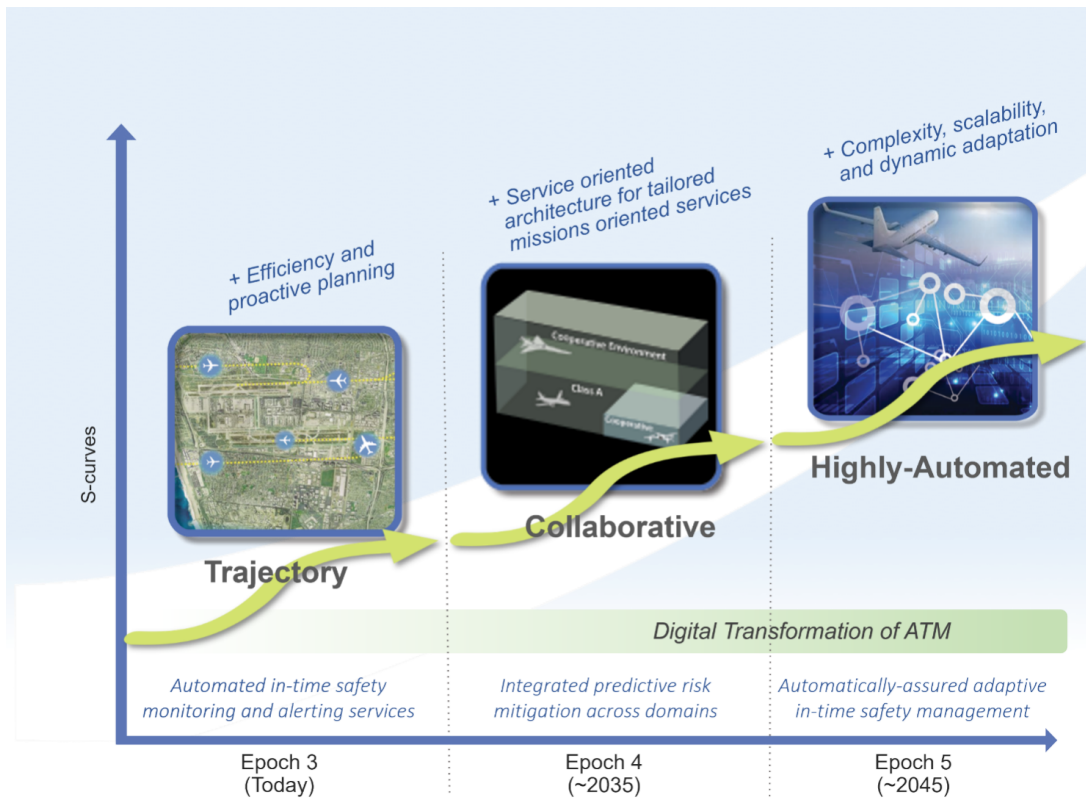


Figure 3. Evolution of Airspace Operations and Safety

19 NASA Sky for All website, <https://nari.arc.nasa.gov/skyforall/>.

Strategic Thrust 1 Outcomes:

1. 2020-2035

Increasingly autonomous and collaborative air traffic management and routine all-vehicle access and operations. Reduced emissions, fuel, noise, and contrails through sustainable aviation operations developed in partnership with government and industry stakeholders. This time frame will see incorporation of increasingly autonomous operations resulting in increased system efficiency, predictability, and reliability gains to further improve operations and support traffic growth, including full integration of technologies developed in the Unmanned Aircraft Systems Traffic Management project.

2. 2035-2045

Dynamic autonomous trajectory services and NAS transformation. This timeframe will see dynamic autonomous trajectory services enabled to yield rapid adaptation to meet user demand or respond to system perturbations. A diverse range of non-traditional vehicles and operations will be integrated into the NAS by means of a scalable, service-oriented architecture, including integration of a diverse range of AAM vehicles and missions in the NAS.

3. Beyond 2045

Transition to a digital service-oriented architecture that is prognostic, collaborative, scalable, and dynamically adaptive for all future users. Highly automated and dynamically adaptable and scalable air transportation operations with automatically assured adaptive in-time safety management to meet the diversity, density, complexity, and volume of future operations. Full safe and seamless integration of autonomous systems into the NAS.

ARMD'S ROLE

The technical focus of Strategic Thrust 1 is on future aviation system concepts, operations, and technologies. ARMD provides two primary roles within this Strategic Thrust. The first is to develop key safety and automation technologies and safety management capabilities that enable and extend the benefits of the FAA plans for NextGen and the future of the NAS. The second role is to look beyond current FAA plans by researching and developing innovative concepts and technologies to ensure that a long-term research base is in place to support future planning, enable transformative approaches to future operations, and safely extend the capabilities and range of uses of the NAS.

ARMD's research for the near-term (2020-2035) will improve NAS efficiency and predictability by delivering technologies to FAA and industry for Info-Centric NAS, as well as continuing progress toward Sky for All by providing enabling technologies that include new air traffic management concepts, real-time predictive modeling and simulation tools integrated with safety assurance, and safe integration of increasingly autonomous operations. Research includes sustainable operations technologies to reduce emissions, fuel burn, noise, and contrails, laying the foundation for collaborative decision making and operations in the NAS and safe and efficient integration of AAM vehicles.

Research aimed at the mid-term (2035-2045) will improve NAS efficiency and predictability by delivering technologies to the FAA and industry that are collaborative and service- and mission-oriented; are highly digital with integrated risk mitigation across domains; and include Machine Learning/Artificial Intelligence-enabled NAS operations. Research includes introduction of integration of autonomous vehicles and safe and efficient integration of ultra-efficient next generation transport category vehicles, as well as high-speed vehicles.

Exploratory research to support the far-term period (later than 2045) will focus on a revolutionary global aviation system with high



A view from the cockpit of a Boeing 787-10 Dreamliner during a series of test flights in 2020 in which NASA tested an air traffic management digital data communications tool known as Tailored Arrival Manager. The tool is designed to detect a potential problem – perhaps bad weather or traffic congestion ahead – generate an efficient new course for the airplane to follow that resolves the problem as it approaches its destination, and then digitally transmit the resulting course change instruction directly to the cockpit. The goal: enable future flight operations to be more fuel efficient while minimizing delays, especially during busy traffic conditions.

Credit: Boeing

levels of autonomy and safety prognostics that demonstrate game-changing efficiencies and enable new markets and vehicles to meet the diversity, complexity, density, and volume of future operations.

Research Themes for Strategic Thrust 1

- **Advanced Operational Concepts, Technologies, and Automation:** Research and development of operational efficiency and enhanced access incorporating proactive safety risk management in operational domains. Validation of air, ground, cloud, and edge architecture, as well as roles/responsibilities that will safely enable sustainable growth, diversity, and density based on expected demand increases.
- **Safety Management for Emergent Risks:** Research and development of prognostic safety risk management solutions and concepts for emergent risks across all vehicles, airspace, and emerging markets.
- **Integrated Modeling, Simulation, and Testing:** Development, validation, and application of advanced modeling, simulation, and testing capabilities to assess and enable scalable, integrated, end-to-end Info-Centric NAS trajectory-based operations functionality, as well as seamless AAM operations and other future aviation system concepts and architectures, some of which will be envisioned by the Sky for All activity.
- **Airspace Operations Performance Enablers:** Advanced research to develop performance requirements and guidelines for enablers, including operational guidelines and standards for new vehicles, secure communications, navigation, surveillance, and information infrastructure requirements, and assuring reliability of safety critical software for integrated, end-to-end global airspace operations and emerging non-traditional markets.

Major Outcome Challenges Addressed by Planned Research

- Research will address overcoming limitations of modeling and testing capabilities used in the development and implementation of advanced solutions for improved capacity, efficiency, and safety.
- Research, development, and implementation of transformational technologies and systems for air traffic management and safety assurance will be critical for meeting projected demand of increased traffic volume and diversity of operations.
- Research that establishes a seamless airspace system without internal barriers, restricted corridors, or segregation between vehicle types and operations that includes systems assessment of airspace, vehicles, and infrastructure capabilities to ensure improved safety, capacity, and efficiency.



NASA's X-59, seen here in this Lockheed Martin illustration, is the centerpiece of the Quesst mission that could make supersonic flight over land possible, dramatically reducing travel time in the United States or anywhere in the world. The X-59 is designed to reduce the loudness of a sonic boom to a gentle thump to people on the ground. It will be flown over select U.S. communities to gather data on human responses to the sound generated during supersonic flight and deliver that data set to U.S. and international regulators. Credit: Lockheed Martin



STRATEGIC THRUST 2: **INNOVATION IN COMMERCIAL HIGH-SPEED AIRCRAFT**

The vision for Strategic Thrust 2 is to achieve practical, affordable, and fully sustainable commercial high-speed air transport over land. High-speed is considered anything greater than the speed of sound, or Mach 1, and less than hypersonic, or Mach 5, in this context. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

COMMUNITY'S VISION

Development of efficient, cost-effective, and environmentally sound commercial high-speed transportation could be a game changer for transcontinental and inter-continental travel. Such a development also would help to sustain U.S. leadership in aeronautical science and technology. The Outcomes for this Strategic Thrust represent an approach to high-speed research focusing on groundbreaking technologies that show promise of overcoming environmental and operational barriers to high-speed commercial aircraft, including use of sustainable aviation fuels.

Environmental barriers include the adverse impacts of sonic boom noise, airport community noise, high-altitude emissions, and high-energy consumption. Successful, fully sustainable, commercial supersonic aircraft must overcome the current prohibition on creating sonic booms over land that was imposed to prevent public annoyance from the unwanted noise. They also must contend with or avoid challenges associated with airport community noise and operationally inefficient subsonic flight segments required for integration with existing air traffic. Of all these barriers, sonic boom noise, which creates an unacceptable impact on both the environment and efficient operations, is viewed as the initial critical barrier to be overcome.

Strategic Thrust 2 Outcomes:

1. 2020-2035

Certification standards identified for supersonic commercial aircraft, including overland flight based on acceptable sonic boom noise, landing and takeoff noise and emissions appropriate for technical and economic viability. The market is opened to new high-speed aircraft for fast point-to-point transportation, with defined standards for manufacturers to measure their product readiness for market entry including acceptable noise characteristics.

2. 2035-2045

Introduction of affordable, low-boom, low-noise, and low-emission commercial supersonic aircraft. It is anticipated that fast point-to-point transportation will first be served by environmentally compatible, small high-speed business jets. This will create new markets and job growth opportunities. Technologies and sub-systems will continue to mature for larger high-speed commercial aircraft.

3. Beyond 2045

Increased mission utility and commercial market growth of high-speed transport fleet. A variety of air transportation markets will be served by such aircraft with capacities as large as 200 passengers that offer rapid travel with competitive economics compared to subsonic air travel, as well as reduced environmental impact.

ARMD'S ROLE

The viability of commercial high-speed service depends, in part, on permissible flight faster than Mach 1 over land and the ability to satisfy the same environmental constraints as those imposed on subsonic aircraft. ARMD's initial technical focus, therefore, is on developing scientifically valid tools and survey techniques to create the necessary database of community response to sonic boom noise. Once the international community has established a sonic boom level acceptable to the public, ARMD research will focus on enabling vehicle designs that achieve the acceptable level, as well as on technologies required to address other environmental and efficiency barriers to development and production of viable high-speed transports.

Because commercial overland supersonic flight is currently prohibited, ARMD's strategy for the near-term (2020-2035) is to focus on enabling establishment of a standard for allowable sonic boom noise levels. ARMD will work with the international standards community to define sonic boom levels based on scientifically valid data on community response to low-noise, high-speed flight over land. In parallel, ARMD research will collect fundamental data on the characteristics of low-noise waveforms in real atmosphere and develop low-boom design tools and models for extrapolating community response to fleet impacts, as well as landing and takeoff analysis tools. ARMD also will identify and explore the additional benefits and challenges to achieve increasing speeds for commercial high-speed aircraft.

ARMD research supporting the mid-term (2035-2045) Outcome objectives will focus on technologies enabling the first and second embodiments of a new generation of high-speed transports, with emphasis on acceptable community and enroute noise and high-altitude emissions, as well as air traffic management technologies and procedures for efficient high-speed and airport terminal operations. Additionally, ARMD will focus on demonstration of technology needed to achieve increasing speeds for commercial high-speed aircraft.

Research objectives beyond 2045 will focus on technologies enabling high-speed transports that are competitive in the airline market, with emphasis on high efficiency and light weight for improved economics, as well as continuing to mature air traffic management technologies for efficient operations.

Research Themes for Strategic Thrust 2

- **Elimination of Environmental Barriers to Commercial High-Speed Aircraft:** Understanding and measuring community response to low sonic booms, minimizing the airport community noise impact of such aircraft, and reducing or eliminating the impact of high-altitude emissions.
- **Integrated Design and Efficiency:** Low-boom design for certification; integrated design for efficiency, performance, and weight reduction; airframe and propulsion technology for improved efficiency, performance, and weight; and sonic boom mitigation technology.
- **Modeling, Simulation, and Test Capability:** Integrated, physics-based models for aircraft design and analysis and quiet wind tunnel and acoustic test facilities.
- **Efficient High-Speed Flight Operations:** Flight systems and cockpit displays for minimized impact of enroute noise, operations for enroute noise impact mitigation, and airspace integration for maximum operational efficiency.

Major Outcome Challenges Addressed by Planned Research

Critical research will generate knowledge and develop technologies capable of supporting the elimination of the 1973 prohibition against flights generating sonic booms over land through the reduction of sonic boom noise to a publicly acceptable level.



NASA will demonstrate high-risk, high-payoff technology advancements critical for U.S. aerospace manufacturers to bring to market innovative, cost-effective, and sustainable products and services demanded by airlines and customers. This truss-braced, high-aspect ratio wing design is one concept of what a sustainable single-aisle commercial transport might look like.

Credit: NASA Illustration



STRATEGIC THRUST 3: **ULTRA-EFFICIENT SUBSONIC TRANSPORT**

The vision for Strategic Thrust 3 is to realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy. It is developed using the community's vision based on priorities identified during dialogue, through strategic analyses, and published consensus reports documenting community-wide goals. It is also informed by the U.S. Aviation Climate Action Plan and includes the Outcomes the aviation community can expect from implementing the results of this ARMD research.

COMMUNITY'S VISION

The aviation community expects that long-haul subsonic transports will provide the bulk of global international and domestic air transportation through at least the 2050s. Sustainable growth to meet the demand for air transportation during these decades calls for safe, economical, energy-efficient, and quiet community-friendly transport aircraft with the payload, speed, and range performance demanded by the market.

Realizing this vision requires the aviation community to accelerate performance improvements in drag, weight, and propulsion to improve energy efficiency and reduce energy consumption. These improvements also must include reducing environmental impacts with goals to reduce emissions of carbon, nitrogen oxides, and noise – all without compromising safety. These goals support reductions in carbon emissions expressed in an International Air Transport Association resolution, and detailed in the Air Transport Action Group Waypoint 2050 report, which calls for achieving net-zero carbon emissions by 2050, while acknowledging the importance of addressing non-carbon impacts from aviation as well. These goals also support meeting and exceeding projected noise and emissions standards recommended by the International Civil Aviation Organization and align with the recommendations of their Committee on Aviation Environmental Protection-sponsored Long Term Aspirational Goal task group as well.

The U.S. government through the FAA released a whole-of-government Aviation Climate Action Plan in November 2021 that aligns with both the U.S. economy-wide climate action plan and international aviation community goals. The plan, graphically shown in Figure 4, describes the aviation sector's path to achieving net-zero carbon emissions by 2050. This goal for the commercial fleet of subsonic aircraft is reliant on diffusion of highly efficient aircraft, extraction of even more efficiency from propulsion systems and aircraft operations, use of drop-in sustainable aviation fuel at scale, and the use of high-integrity emission offsets if expected efficacy of sustainable fuels to reduce life-cycle CO₂ is not realized. Today, sustainable fuels are the only operationally practical option available for the existing and near-term, entry-into-service fleet that could significantly help meet the net-zero carbon gas emissions goal by 2050; mid-term aircraft and propulsion systems will substantially reduce energy consumption, reduce emissions, and reduce requirements for sustainable aviation fuel. The plan recognizes challenges in the sustainable fuels supply chain and the large uncertainty in their actual potential. In addition, the plan also recognizes the climate impact from non-CO₂ emissions and contrails.

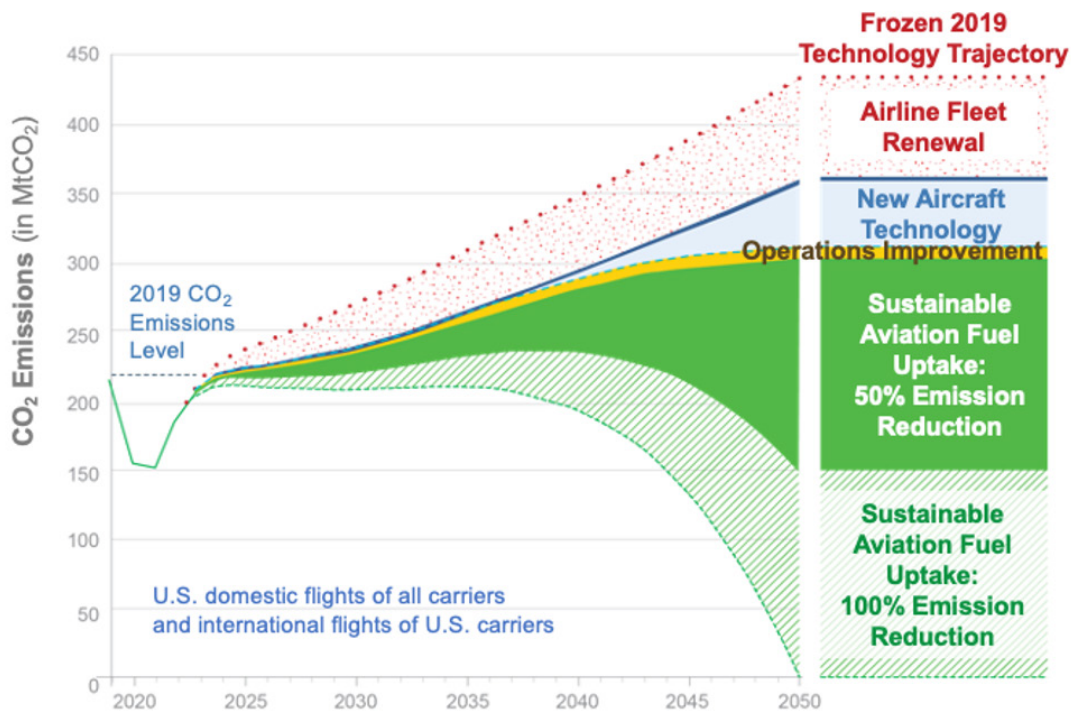


Figure 4. U.S. Aviation Climate Action Plan Path to Net-Zero: Aviation Carbon Emissions by 2050

Strategic Thrust 3 Outcomes:

1. 2020-2035

Aircraft meet efficiency, economic, and environmental demands of airlines and the public, and are on a defined path to fleet-level net-zero carbon by 2050 with reduced community noise and harmful emissions, including the use of high-integrity, non-aviation carbon offsets. Technology solutions demonstrated, understood, and ready to incorporate into next generation design. Non-CO₂ environmental impacts from aviation understood. Research continues for fully zero harmful emission propulsion architectures and subsystems using non-carbon-based fuels for various missions.

2. 2035-2045

Aircraft meet economic demands of airlines and the public with revolutionary improvements in energy efficiency with reduced community noise and harmful emissions and are on an accelerated path toward fleet level net-zero carbon emissions with reduced non-CO₂ impacts and reliance on carbon offsets. Initial applications of advanced airframe technologies emerge in conjunction with new propulsion architectures such as electrified aircraft propulsion.

3. Beyond 2045

Aircraft meet economic demands of airlines and the public with transformational capabilities powering aviation to net-zero carbon emissions and beyond through improved energy efficiency, with further reduced community noise and harmful emissions. Aircraft and propulsion systems leverage a modernized clean energy infrastructure with reliance on carbon offsets and non-CO₂ impacts minimized.

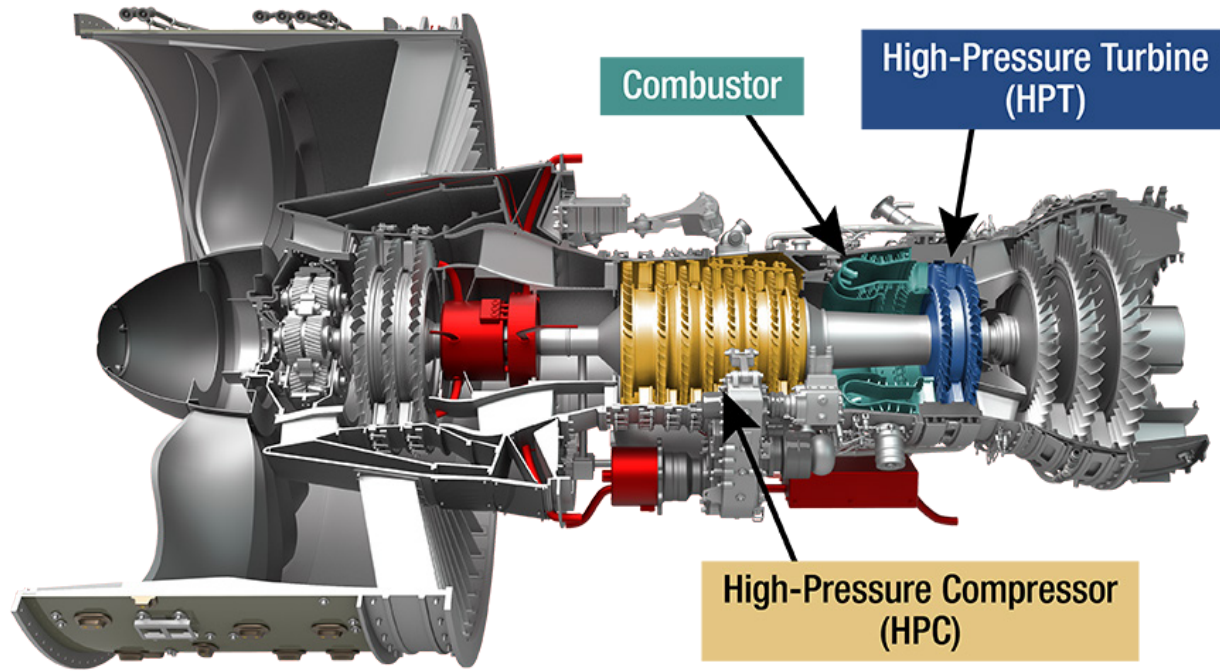
ARMD'S ROLE

ARMD's overarching strategy is to remove barriers and address high-risk technical challenges in lockstep with the community's vision and their progress toward that vision. ARMD will work with industry to mature promising tools and technologies to meet near-term economic and environmental needs, enabling community Outcome 1, while accelerating development of the promising technologies that will enable new aircraft products for Outcome 2, and exploring and identifying the most likely technologies to achieve Outcome 3.

This Strategic Thrust focuses on aircraft technologies and the use of cleaner energy, while Strategic Thrust 1 focuses on air traffic operational efficiency improvements. Aircraft technology research will focus on advanced airframes to improve aerodynamic and structural efficiencies and transformational propulsion capabilities – such as electrified aircraft propulsion – coupled with more efficient gas turbine engines. The focus will be on long-haul domestic and international commercial transports, which dominate aviation's impact on the environment. Opportunities also will be sought to transition these capabilities to operations in short-haul and regional markets as early as possible.

NASA has researched the use of renewable energy sources and alternate fuels for decades and is fully committed to supporting the application of sustainable aviation fuels to the commercial fleet.

ARMD's approach to enabling community Outcomes is to work with the aviation community to accelerate development of advanced technologies in the near term while pioneering revolutionary technologies and integrated vehicle systems and concepts. Together with the aviation community, ARMD will explore advanced vehicle concepts and enabling technologies capable of achieving these improvements. Conceptual designs responding to specific levels of performance provide an avenue to rapidly assess different technologies' impact on attributes of a vehicle design under various scenarios and constraints, as well as their dependencies on other technologies. The conceptual designs also



NASA's Hybrid Thermally Efficient Core project is seeking to make the aviation industry more sustainable by developing a small core for a turbofan jet engine that increases fuel efficiency. The project also includes work on hybridization – developing methods to pull more electrical power from the engine to power other systems aboard the aircraft, which could increase fuel efficiency in much the same way a hybrid car does.

Credit: NASA Illustration

enable comparisons of performance, technical risk, and other attributes of advanced vehicle concepts. In addition, the research will ensure the safety implications of advanced technologies and concepts are identified and considered in the development process.

Innovative concepts, technologies, and methods with the highest potential impact will be prioritized for further development. ARMD will explore and develop these game-changing concepts, technologies, and methods, and then verify their practicality via large-scale ground and/or flight-based demonstrations in partnership with industry to facilitate technology transfer into commercial products.

In addition, ARMD will continue to develop and validate enabling tools, methods, and processes (e.g., advanced computational methods, innovative materials, and structures). The result will be a base of evolving research and technology for the next generations of vehicles that will be developed and produced by industry. ARMD will continue partnering with industry, academia, the FAA, and other government agencies for research in specific areas for early transition to immediate near-term market opportunities. Additionally, ARMD will continue to support fundamental improvements in vehicle modeling, design, test, and evaluation, as well as advances in aerodynamics and aeromechanics, propulsion, and use of composites and other advanced materials.

Research Themes for Strategic Thrust 3

- **Ultra-Efficient Airframes:** Research and development of technologies to enable new airframe systems with high levels of aerodynamic performance, lower structural weight, and innovative approaches to noise reduction, with opportunities to integrate alternative energy subsystems.
- **Ultra-Efficient Propulsion:** Research and development of technologies to enable new propulsion systems with high levels of thermal, transmission, and propulsive efficiency, reduced harmful emissions, and innovative approaches to noise reduction and opportunities to transition to alternative energy sources.
- **Ultra-Efficient Vehicle System Integration:** Research and development of innovative approaches and technologies to reduce perceived noise and aircraft energy consumption through highly coupled, synergistic vehicle system integration including, but not limited to, propulsion-airframe integration and integration of alternative energy subsystems.
- **Modeling, Simulation, and Test Capability:** Research and development of computational, experimental, and analytical tools and methods to improve vehicle mission capability in less time with reduced uncertainty and cost.

Major Outcome Challenges Addressed by Planned Research

- Research and integrated demonstration dramatically reduce technical and financial risk to industry to introduce revolutionary, advanced technology into products. Without research and integrated demonstration, technology infusion into future products would be slow and/or less impactful, resulting in the industry being unable to advance at the pace needed to achieve economic and environmental community-defined goals and Outcomes.
- Without research through integrated technology demonstration, international competitors could gain an advantage over U.S. industry, especially if international environmental regulations advance more rapidly than technology. Moreover, such regulations could be costly to U.S. airlines, resulting ultimately in increased costs to the flying public.



An idea for a future air taxi hovers over a theoretical municipal vertiport in this NASA illustration. Several local governments have been working with NASA through a series of workshops to prepare their transportation plans to include this new form of air travel.

Credit: NASA / Lillian Gipson and Kyle Jenkins



STRATEGIC THRUST 4: **SAFE, QUIET, AND AFFORDABLE VERTICAL LIFT AIR VEHICLES**

The vision for Strategic Thrust 4 is to realize extensive use of vertical lift vehicles for transportation and services including new missions and markets. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

COMMUNITY'S VISION

The aviation community expects a radical increase in new and cost-effective uses of aviation to provide travelers the flexibility to fly when and where they want in a fraction of the time it takes today. This flexibility is expected to greatly increase demand for air service and significantly increase the number of flights. Transportation by vertical lift aircraft could prove to be faster and more convenient relative to ground transportation. To reach widespread use, however, the flights must be safe, operate with a significantly reduced environmental footprint, and generate acceptable noise to the surrounding communities.

Public demand for increased mobility will be met in part by vertical lift air vehicles developed to operate over a wide range of configurations and missions. These configurations will provide unmatched access to urban transportation and services (e.g., air taxi, air metro, and personal air vehicles). They also will make unique missions and public good services available across a spectrum of applications (e.g., cargo delivery, emergency medical services, and disaster relief). Many of the unique missions will require various levels of automation and autonomy for both air vehicles and airspace, and they also will require noise and emissions to be non-intrusive when operating near people and property.

Strategic Thrust 4 Outcomes:

- 1. 2020-2035**
Increased capability of new vertical lift configurations with reduced environmental impact and improved safety and accessibility for new and current markets.
- 2. 2035-2045**
New vertical lift configurations and technologies introduced that enable expanded markets, improve reliability, increase mobility, enhance accessibility, and reduce environmental impact.
- 3. Beyond 2045**
Vertical lift vehicles of all sizes routinely used for widespread transportation and public good services in successfully developing markets, and that feature mature mobility and accessibility with demonstrated low environmental impact.

ARMD'S ROLE

ARMD's overarching strategy is to remove barriers and address high-risk technical challenges in lockstep with the community's vision and progress toward that vision. ARMD will work with industry to mature promising vertical lift vehicle technologies to meet near-term needs, enabling the first community Outcome, while developing promising technologies that will enable new vertical lift vehicle products that meet or exceed mid- and far-term metrics, allowing industry to achieve the second and third community Outcomes.

ARMD near-term (2020-2035) research for vertical lift vehicles aims at key capabilities and technologies that directly benefit vertical lift aircraft and enable markets for industry and government. NASA research will identify and recommend methods to mitigate the noise impact on communities and include validating analysis tools and evaluation of promising technology concepts for noise and safety.

Mid-term (2035-2045) research focuses on key technologies that will enable U.S. industry to expand the global vertical lift vehicle market while setting new standards in noise, safety, reliability, and performance. The most promising technologies will be prioritized and explored, and the results will be transferred to the community.

Far-term (Beyond 2045) vertical lift research is aimed at capabilities and technologies that will eliminate barriers for quiet, safe, efficient, autonomous vehicles operating in both urban and rural environments. This research will focus on the integration of technologies and concepts to improve the entire ecosystem for vertical lift configurations.

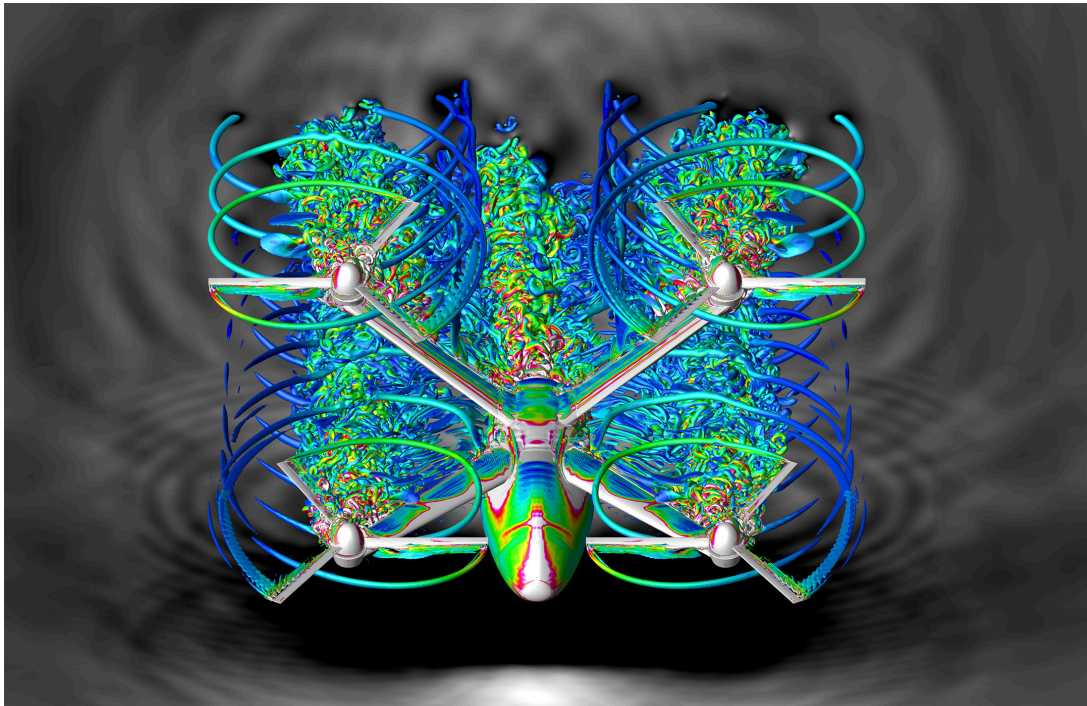
Research Themes for Strategic Thrust 4

- **Clean and Efficient Propulsion:** Research and development advancing the safety, reliability, and efficiency of propulsion systems and expanding integration and development of alternative propulsion systems for vertical lift configurations.
- **Efficient and Quiet Vehicles:** Research and development of technologies and configurations that optimize performance and speed and minimize noise and cost.

- **Safety, Comfort, and Accessibility:** Research and development of technologies and capabilities that improve passenger and public safety during operations, enable the aircraft to better respond to flight conditions such as turbulence (passenger comfort), as well as operational concepts that improve access to transportation and services for everyone.
- **Modeling, Simulation, and Test Capability:** Research and development of computational, experimental, and analytical tools and methods to allow rapid design, development, and validation of a broad range of innovative vertical lift air vehicles.

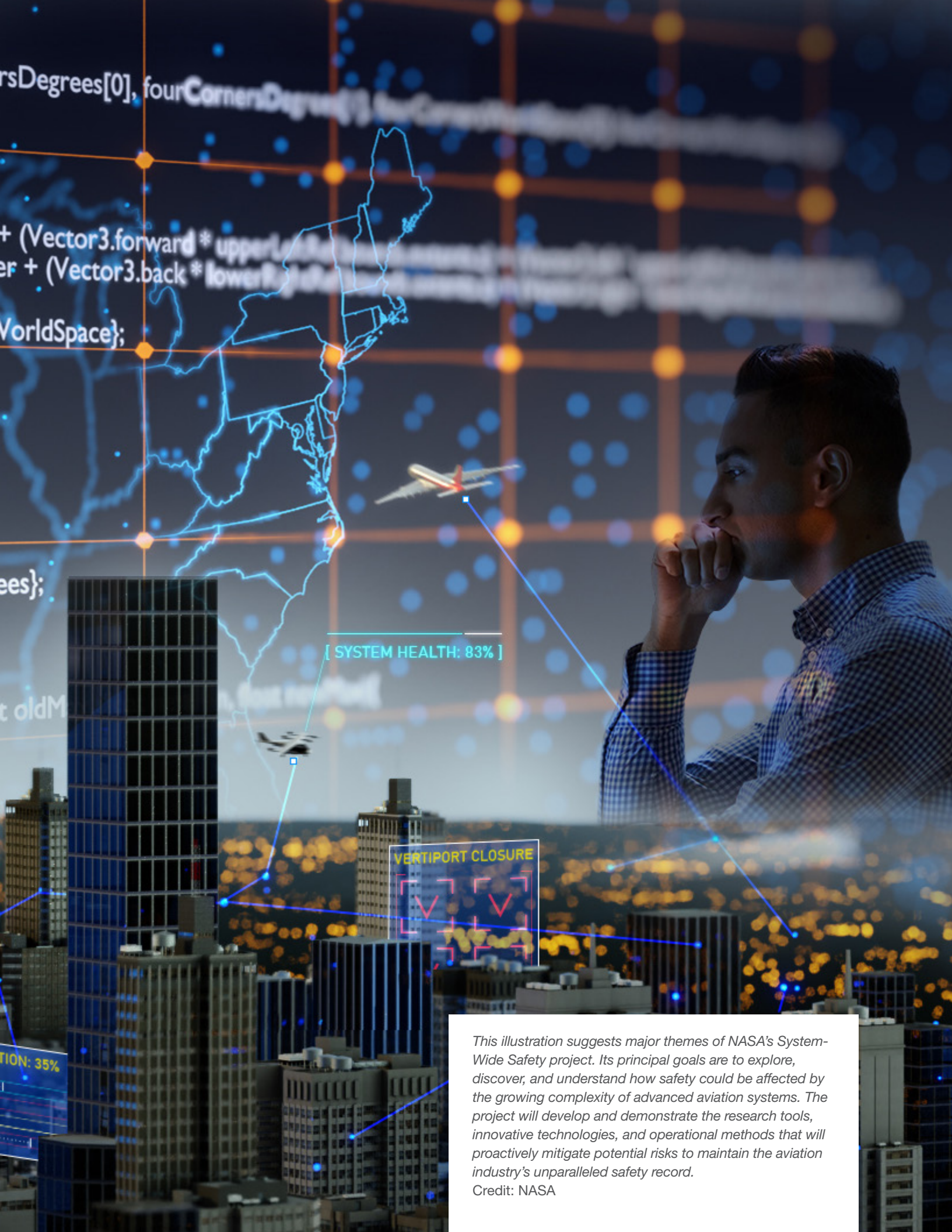
Major Outcome Challenges Addressed by Planned Research

- Research will be critical to reduce uncertainties associated with vertical lift vehicle safety and noise and to develop recommendations for standards for certification and operations.
- Research and technology development will be critical to progress advanced design capabilities and enable industry to develop and produce a broad range of innovative vertical lift air vehicles that operate safely and quietly.



A concept for a six-passenger quadcopter is run through a computer simulation to visualize the interaction of airflow among the four rotors. Among the design goals are to minimize the interaction between the front and rear rotors, while keeping an efficient and compact configuration. The Pleiades and Electra supercomputers at NASA's Ames Research Center in California were used to process the hundreds of millions of data points that are the result of four three-bladed rotors rotating and slightly flexing.

Credit: NASA / Patricia Ventura Diaz



This illustration suggests major themes of NASA's System-Wide Safety project. Its principal goals are to explore, discover, and understand how safety could be affected by the growing complexity of advanced aviation systems. The project will develop and demonstrate the research tools, innovative technologies, and operational methods that will proactively mitigate potential risks to maintain the aviation industry's unparalleled safety record.

Credit: NASA



STRATEGIC THRUST 5: **IN-TIME SYSTEM-WIDE SAFETY ASSURANCE**

The vision for Strategic Thrust 5 is the ability to predict, detect, and mitigate emerging safety risks throughout aviation systems and operations. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

COMMUNITY'S VISION

Decades of continuous efforts to reduce risk in commercial aviation have made it the safest mode of transportation. By addressing known hazards and responding to issues illuminated by analysis of incidents and accidents, commercial aviation has achieved exemplary safety records and inspired the confidence of the flying public. As aviation adopts new technologies to enhance the capacity, efficiency, and uses of the NAS, maintaining a safe system will require recognition and timely mitigation of emerging safety issues before they become hazards. A shift toward proactive risk mitigation will become critical to meet these needs.

This Strategic Thrust will deliver a progression of capabilities to accelerate the proactive detection, prognosis, and resolution of emergent threats to system-wide safety. The result will be an in-time aviation safety management system (IASMS) that utilizes system-wide data to provide alerting and mitigation strategies in real-time to address emerging risks.

Strategic Thrust 5 Outcomes:

1. 2020-2035

Give more users better access to safety-relevant data to allow for system-wide monitoring and enable predictive technologies. Integration of heterogeneous data from the entire system will allow for a more comprehensive understanding of risks, including in-time detection and alerting capabilities available to operators across the NAS.

2. 2035-2045

Introduction of an IASMS that continuously monitors the NAS – and sub-elements within the NAS – to collect data on the status of all elements and operators within the NAS. The IASMS will accommodate new operations and new capabilities as they are introduced into the system, detecting new risks as they emerge.

3. Beyond 2045

Adaptive in-time safety threat management will incorporate increasingly autonomous human-machine decision support to enable proactive prediction and mitigation of risk in complex operations and support NAS-wide safety assurance.

ARMD'S ROLE

Strategic Thrust 5 focuses on research that incorporates secure sensor and networking technologies, along with innovative data access, data analytics, and decision support methods to enable unprecedented insight into system operations, health, and safety. System-of-systems modeling, prognostic tools, and run-time system assurance technologies will enable real-time, system-wide safety assurance.

In the near-term (2020-2035), ARMD research will focus on continuous availability of data for real-time monitoring, real-time anomaly, and precursor identification, as well as initial integration of data to provide a comprehensive view of emerging risks to various operators in the system as envisioned by the Info-Centric NAS. Research will focus on automated safety and security data analytics to support monitor and alert actions.

Research for the mid-term (2035-2045) will enable introduction of an integrated IASMS that provides system-wide continuous monitoring of safety margins and trustworthy decision support tools that manage uncertainty to enable in-time hazard mitigation. Research will ensure that the emerging concepts, architecture, technologies, and procedures related to Sky for All are safe and assured.

Beyond 2045, ARMD research will focus on intelligent safety monitoring through highly automated Machine Learning- and Artificial Intelligence-enabled IASMS for dynamic human-automation hazard mitigation strategies.

Research Themes for Strategic Thrust 5

- Continuous System-Wide Safety Awareness (Monitor): Technical approaches and required architecture to support comprehensive continuous safety monitoring through acquisition, integration, and assurance of sensitive data from heterogeneous sources.
- Safety Risk Identification and Evaluation (Assess): Assured tools that improve the accuracy of real-time detection, diagnosis, and prediction of hazardous states and the impact of these states on system safety.
- Coordinated Prevention, Mitigation, and Recovery (Mitigate): Trusted methods for dynamic, multi-agent planning, evaluation, and execution of real-time risk mitigating response to hazardous events.
- Experimentation, Demonstration, and Assessment: Experimentation, demonstration, benefits analysis, and transition of new In-Time System-Wide Safety Assurance technologies to the NAS.

Major Outcome Challenges Addressed by Planned Research

- Research, technology development, and implementation of validated tools and effective real-time monitoring will be critically dependent on access to sensitive data from all elements of the system. Trust and confidence within the community, dependent largely on the effectiveness of processes and tools to provide data protection, are additional non-technical aspects enabling a successful Outcome.



The System-Wide Safety project is one of several supporting NASA's Advanced Air Mobility mission to help make it a reality. One effort is developing the In-time Aviation Safety Management System, which can automate safety assurance and risk management functions performed manually today. This concept illustration shows how elements of automation could be integrated into a future airspace.

Credit: NASA Illustration



An illustration of an urban air mobility environment, where air vehicles with a variety of missions — with or without pilot —, are able to interact safely and efficiently.
Credit: NASA / Lillian Gipson



STRATEGIC THRUST 6:

ASSURED AUTONOMY FOR AVIATION TRANSFORMATION

The vision for Strategic Thrust 6 is to safely implement autonomy in aviation applications. It is achieved using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

This Strategic Thrust incorporates recommendations of the National Academies report, *Autonomy Research for Civil Aviation*. The report established the concept of increasing autonomy and identified NASA's role as supporting basic and applied research in civil aviation technologies, including air traffic management technologies of interest to the FAA. NASA seeks to ensure autonomy technologies for traditional aviation applications that unequivocally show improvements in overall safety without sacrificing other factors. Similarly, for novel aviation missions, automation and autonomy technologies must ensure enabling their business cases AND safe integration of novel vehicles and missions into the NAS.

COMMUNITY'S VISION

The evolution of autonomous systems will transform aviation, providing improvements in safety, efficiency, and flexibility of operations to increase the capacity, robustness, and flexibility of the NAS. Additional benefits will be realized through new uses of the airspace – enabled by advances in autonomy – such as AAM operations, including on-demand personal air transportation.

Strategic Thrust 6 Outcomes:

1. 2020-2035

Initial safe and efficient integration of highly automated vehicles into the NAS by introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals. Starting from wildfire management, increasingly autonomous air and ground systems will enable 24/7 continuous aerial surveillance and suppression, and not be limited to visual meteorological conditions that exists today. This period will also see the introduction of initial adaptive automation functions within airborne and ground-based systems, assured by limiting envelopes of applicability. New capabilities enabled by use of autonomous systems will be introduced, especially for AAM applications.

2. 2035-2045

Ubiquitous integration of increasingly autonomous vehicles into the NAS by introduction of aviation systems with flexible autonomy based on earned levels of trust and capable of carrying out mission-level goals. Feasibility validation of new air, ground, and cloud edge architecture that will enable the density, diversity, and complexity of airspace operations expected in 2045 and beyond. Systems will learn and adapt through access to large quantities of data, enabling sophisticated world models of system states and operating environments.

3. Beyond 2045

Introduction of distributed collaborative aviation systems with assured autonomy capable of carrying out policy-level goals. Society will gain high confidence in autonomous aviation systems, and large-scale autonomous systems will achieve goals specified at levels of system governance and sustainability. System elements will be distributed and collaborative, enabling unprecedented efficiency, agility, robustness, and resilience.

ARMD'S ROLE

The focus of Strategic Thrust 6 is to provide game-changing benefits of autonomy for civil aviation through use of machine intelligence and machine connectivity. ARMD will leverage rapidly evolving developments in machine learning, robotics, and adaptive, cognitive computing architectures to enable high-impact autonomy applications. These efforts will be complemented by extensive research and development of methods and capabilities to validate and assure trusted performance of highly complex systems-of-systems with substantial adaptive characteristics. Special focus will be placed on assessing the ability of machine learning functions to adapt to emergent conditions.

ARMD's primary role will be in development of concepts, architectures, and applications for autonomous aviation systems, as well as addressing critical autonomy barriers that require unique NASA contributions. Research will include development of mission products that leverage the widespread growth and rapid development cycles of AAM. ARMD will provide community coordination and leadership to achieve research advances, implement selected applications, and leverage large investments in non-aviation autonomy technologies by adapting those technologies for aviation.

In the near-term (2020-2035), ARMD research will focus on mission-level, goal-directed adaptive automation, large-scale detailed world views using advanced sensors and networks, human/machine teams with differing allocations of control depending on specific situations, and extensive machine-based learning applied to large-scale integrated systems. Research will initially deliver system-level logical architecture along with functional and performance requirements; then reference vehicle, airspace, and safety automation technologies for medium-density and medium-complexity AAM operations; culminating in technologies and architecture requirements for high-tempo/high-density/high-complexity urban AAM operations. Research will focus on validation and verification of complex systems and assurance of automated systems. Research will deliver Integrated Concept of Operations and increasingly autonomous technologies to U.S.

government partner agencies and industry for Advanced Capabilities for Emergency Response Operations to use in aerial mitigation of wildfire threats and integration of surveillance and sensing data from NASA's Science Mission Directorate.

Research for the mid-term (2035-2045) will focus on automated trajectory negotiation, safe and efficient integration of heterogeneous and increasingly autonomous vehicles, validation and verification, and assurance of autonomous systems. Research also will include adaptive automation deployed within and across diverse architectures – including onboard, cloud, and ground systems – which are able to learn and continually improve.

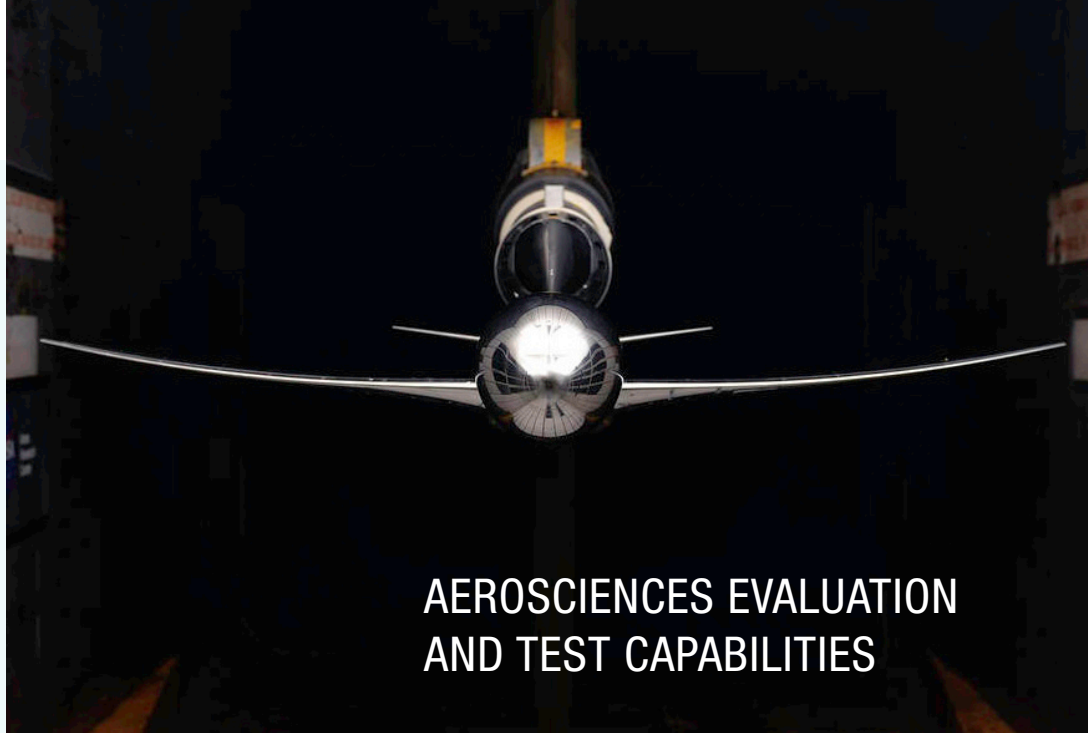
Research for the far-term (beyond 2045) will aim at extreme flexibility and adaptability for large-scale systems, with extreme levels of reliability and recovery from disturbances. Research topics include campaign-level, goal-directed adaptive automation embedded within all system elements; adaptive collaboration based on extensive shared world views; highly distributed large-scale collaborative systems that constitute integral parts of larger systems they support; and human/machine teams, with humans primarily specifying strategic goals.

Research Themes for Strategic Thrust 6

- Technologies and Methods for Design of Complex Autonomous Systems: Methods and technologies for design of intelligent machine systems capable of operating and collaborating in complex environments.
- Integrated Modeling, Simulation, and Testing: Development, integration, advanced modeling, and validation of system architectures and capabilities to enable diverse and scalable end-to-end operations, including seamless integration of AAM operations and improved sustainability to traditional operations.
- Assurance, Verification, and Validation of Autonomous Systems: Methods for certification and assuring trustworthiness in the design and operation of autonomous systems.
- Human-Autonomy Teaming in Complex Aviation Systems: Optimal human-machine role assignments and teaming strategies for increasing machine autonomy and earned levels of trust.
- Implementation and Integration of Autonomous Airspace and Vehicle Systems: Novel real-world autonomy applications and transition paths toward higher levels of autonomy.
- Testing and Evaluation of Autonomous Systems: Metrics, models, simulation capabilities, and testbeds for assessment of autonomous systems in laboratory and operational settings.

Major Outcome Challenges Addressed by Planned Research

- Relevancy of research will be critically dependent on maintaining awareness of unknown issues, risks, and opportunities through strategic partnerships.
- Without overcoming verification and validation challenges, technology infusion into future products would be slow, resulting in the industry being unable to advance at the pace needed to achieve the community Outcomes.



AEROSCIENCES EVALUATION AND TEST CAPABILITIES

Obtain aerodynamic and flow visualization data on a generic transport model to assess the performance of computational fluid dynamics codes used throughout the aerospace community.

Credit: NASA

As part of ARMD, the Aerosciences Evaluation and Test Capabilities portfolio office executes strategic efforts to preserve and enhance research and test capabilities for NASA's world-class collection of national wind tunnel facilities. These facilities are paving the way toward the future by offering versatile and comprehensive ground testing in the area of technology innovation while providing new capabilities, calibration, and characterization through our diverse and highly skilled workforce.

The portfolio's assets include capabilities in the subsonic, transonic, supersonic, and hypersonic speed regimes as well as propulsion test facilities at NASA field centers in Virginia, Ohio, and California. State-of-the-art testing support is a crucial component in the advancement of innovative technologies that will facilitate ARMD in executing the Strategic Implementation Plan.



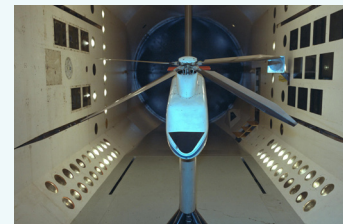
NASA contractor Sam Lee uses a 3D laser scanner to measure the ice shape that was generated in the Icing Research Tunnel on a large-scale wing section at NASA's Glenn Research Center in Cleveland.

Credit: NASA



Greg Gatlin, an aerospace research engineer from NASA's Langley Research Center in Virginia, inspects a scale truss-braced wing during testing in the Unitary Plan Wind Tunnel complex at NASA's Ames Research Center in California.

Credit: NASA



A rotorcraft model sits on a test stand in the Transonic Dynamics Tunnel at NASA's Langley Research Center in Virginia. The wind tunnel is dedicated to identifying, understanding, and solving aeroelastic issues confronting fixed-wing aircraft, helicopter, and tiltrotor configurations.

Credit: NASA

CROSSCUTTING RESEARCH, WORKFORCE DEVELOPMENT, AND TEST CAPABILITIES

In addition to research that directly aligns with specific Strategic Thrusts, NASA's ARMD conducts foundational research on crosscutting ideas and technologies that provides critical support across multiple Strategic Thrusts for both near- and long-term goals. This research enables a broad range of aeronautics and aerospace applications and explores opportunities for technology convergence from disparate technology areas. Flight and ground capabilities for experimentation and feasibility demonstrations are additional elements that support the research for multiple Strategic Thrusts.

For NASA Aeronautics to be truly transformative, rapid exploration and characterization of high value, convergent opportunities in collaboration with the traditional and emerging U.S. aviation community is critically important. ARMD's crosscutting research looks for new aeronautics solution spaces and embraces the convergence of perspectives, technologies, and disciplines to explore these spaces in ways that others are not. NASA's innovative workforce seeks to discover new ways to overcome barriers and challenges that will enable our sustainable aeronautics future beyond the needs of today. As NASA works with our expanding aeronautics community, we will use the insights gained from these engagements to build a research portfolio that addresses industry needs and where NASA invests in research vital to ensuring our continued role as global leaders.

Crosscutting investment falls mainly into three areas that are broadly critical to advancing ARMD long-term strategic outcomes: (1) next-generation, physics-based and data-driven modeling and design capabilities to enable realization of long-term vehicle and aviation system design concepts, including new air traffic management paradigms; (2) transformational flight capabilities through innovations in discipline-oriented technologies such as radically new types of strong and lightweight materials, measurement techniques, autonomy concepts, experimental methods, and approaches for electrification of aviation; and (3) education and supporting development of the next generation of aeronautical innovators.

Research Tools

Research in state-of-the-art computational and experimental tools and technologies seeks to develop multidisciplinary computational capabilities for modeling a broad range of phenomena of interest to aeronautics, including turbulent, high-speed, and reacting flows; acoustics; and all aspects of fluid physics – as well as development and validation of autonomous vehicle system control concepts enabling rapid progress from concept to flight.

Transformational advances in discipline-oriented technology areas, such as materials, measurement techniques, and flight and propulsion controls, are required to enable advanced vehicle and propulsion system concepts for the future. Innovative measurement techniques, including optical techniques for both surface and off-body measurement, will improve diagnostic capability, as well as provide the advanced measurement capability needed for the validation experiments supporting development of tools and methods.

Fundamental research on reducing the barriers to reusable ultra-high-speed vehicle systems provides one example of incorporating advancements across multiple disciplines to support an application. ARMD will conduct fundamental research to enable a broad spectrum of systems and missions by advancing the core capabilities and critical technologies for ultra-high-speed flight.

Analytical tools, test techniques, and fundamental capabilities will reduce the barriers to routine, reusable ultra-high-speed flight. Research here will enable ARMD to create system-level design and analysis capabilities to enable more definitive systems analysis with quantified uncertainty, as well as developing and demonstrating key propulsion capabilities and technologies necessary to enable mode transition for combined-cycle ultra-high-speed propulsion systems.

ARMD also will address more foundational challenges associated with aerodynamic heating, boundary layer transition, and overall thermal management. Advances will continue in computational fluid dynamics for high enthalpy, chemically reacting flows. Research and development in high-temperature durable materials, dynamic seals, and sensor technologies will help to make reusable ultra-high-speed vehicles a reality.

Workforce Pipeline

Key to realizing mission success for everything ARMD envisions will be engaging, invigorating, and training the next generation of engineers.

Opportunities are provided for university-led teams to conduct research in transformative technologies that supports NASA Aeronautics' major research goals. These opportunities include the University Leadership Initiative and the University Student Research Challenge. Inspiring and investing in universities at the faculty level and student researcher level to take on a larger leadership role in advancing ideas, while training the future workforce, will transform aviation and maintain U.S. leadership in the global aviation community.



Carnegie Mellon University won first place in the 2022 Blue Skies Competition with their project Sustainability and Connected Autonomy: A New Era for Aviation. Team members, from left to right, include: Aaron Burns, Jaona Jacob, Shruti Prasanth, Ashima Sharma, and Tahaseen Shaik.

Credit: NASA

A variety of aeronautical design challenges for younger students also are offered. Not only do these activities encourage developing scientific and engineering skills, there also are opportunities for writers, artists, and even budding entrepreneurs to participate. The message is clear: it takes people with talents and skills of every kind to help NASA achieve its goals.

Research Infrastructure

ARMD's flight and ground test capabilities, complemented by high-fidelity computational simulation, enable rapid experimentation and feasibility demonstration of advanced concepts ranging from individual experiments and proof-of-concept tests to demonstration of integrated concepts embodying converging technologies. Relevant assets include flight research and support aircraft; wind tunnels; propulsion, acoustic, materials, and structures laboratories and test facilities; flight research and air traffic management simulators; airspace operations laboratories; high-end computing laboratories; and test support infrastructure. These facilities and capabilities will continue to evolve in support of the research necessary to address the Strategic Thrusts. Also, innovative measurement techniques will be researched and developed for rapid high-level assessment of stresses, flow dynamics, and thermal behavior of test articles.

Air transportation is an integral part of modern life, providing safe, affordable, and convenient travel to the public.

SUMMARY

Air transportation is an integral part of modern life, providing safe, affordable, and convenient travel to the public. In a 2020 economic impact report published by the Federal Aviation Administration, air travel accounted for \$1.8 trillion of total U.S. economic activity, supporting nearly 11 million direct and indirect jobs. Of those, more than one million were high-quality manufacturing jobs. Aviation has proven to be resilient to catastrophic setbacks (e.g., COVID-19) as latest transportation data indicates a returning of business and leisure travel.

NASA's aviation research – carried out by the Aeronautics Research Mission Directorate – will play a leading part in enabling an air transportation system that meets global needs through 2045 and beyond. These needs are shaped by three Mega-Drivers: global growth in demand for even faster mobility; affordability, sustainability, and energy use; and technology convergence.

To continue NASA's leadership in aviation innovation and enable a revolutionary transformation of the aviation system, ARMD's research portfolio is focused on six Strategic Thrusts:

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial High-Speed Aircraft
- Ultra-Efficient Subsonic Transport
- Safe, Quiet, and Affordable Vertical Lift Air Vehicles
- In-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

ARMD's strategic planning emphasizes enabling the achievement of Outcomes expressed as societal or economic benefits within these Strategic Thrusts. ARMD research will leverage new and non-traditional technologies and approaches, including alternative fuels and electric or hybrid propulsion, low-boom supersonic flight, automation and autonomy, and technology convergence to develop transformative solutions.

The ultimate goal is to enable a safe, efficient, adaptable, and environmentally sustainable global aviation system – including net-zero carbon emissions by 2050 and eventually fully zero harmful emissions – to meet the challenges of the future.

JOIN THE CONVERSATION

This SIP is a living document through which NASA communicates with stakeholders and the research community. Feedback is welcome and encouraged and can be sent to hq-armd-strategy@mail.nasa.gov.



In this illustration, a drone flies within a smoke-filled sky, providing firefighters on the ground with information that will help them more quickly adapt to rapidly changing conditions. NASA is working with its partners in government, industry, and academia to apply unmanned aircraft and air traffic management technologies developed by several ARMD projects to wildfire management and mitigation.

Credit: NASA / Daniel Rutter

ACRONYMS AND INITIALISMS

AAM	Advanced Air Mobility
ARMD	Aeronautics Research Mission Directorate
CO ₂	Carbon Dioxide
FAA	Federal Aviation Administration
IASMS	In-Time Aviation Safety Management System
ISSA	In-Time System-Wide Safety Assurance
NACA	National Advisory Committee for Aeronautics
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
SIP	Strategic Implementation Plan

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