National Aeronautics and Space Administration

NASA AERONAUTICS

Strategic Implementation Plan

2017 Update

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Executive Summary

This Strategic Implementation Plan sets forth the NASA Aeronautics Research Mission Directorate (ARMD) vision for aeronautical research aimed at the next 25 years and beyond. It encompasses a broad range of technologies to meet future needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation.

Long-term aeronautics research has long provided the basis for new concepts leading to industry innovation and societal benefits. The future holds new challenges for the aviation system, including the need to achieve continued growth that meets increasing global demand, to safely integrate unmanned aircraft systems and other innovative vehicle concepts with myriad applications, and to proactively adapt to changing conditions. An overarching challenge is to solve those challenges in ways that have minimum adverse impact on the environment.

Analysis of global trends has led ARMD to identify the following three overarching drivers, referred to as Mega-Drivers, which will in large part shape the needs for aeronautical research in the coming years:

- Mega-Driver 1, Global Growth in Demand for High-Speed Mobility: Reflects rapid growth in traditional measures of global demand for mobility.
- Mega-Driver 2, Affordability, Sustainability, and Energy Use: Presents severe challenges in maintaining affordability and sustainability.
- Mega-Driver 3, Technology Convergence: Points to convergence occurring in industry sectors such as materials, manufacturing, energy, and information and communication technologies that will transform aeronautical capabilities.

Six Strategic Thrusts represent ARMD's response to the Mega-Drivers as they affect aviation:

- Strategic Thrust 1: Safe, Efficient Growth in Global Operations
- Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft
- Strategic Thrust 3: Ultra-Efficient Commercial Vehicles
- Strategic Thrust 4: Transition to Alternative Propulsion and Energy
- Strategic Thrust 5: Real-Time System-Wide Safety Assurance
- Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Taken together, these Strategic Thrusts constitute a vision for the future of aviation. ARMD's strategic planning addresses research needs associated with these Strategic Thrusts through a hierarchy of Outcomes, Research Themes, and Technical Challenges. Outcomes defined in terms of in-service capabilities and benefits in three time frames — near-term (2015 to 2025), mid-term (2025 to 2035), and far-term (>2035) — signify the advances required to address each Strategic Thrust. Research Themes, which support the Outcomes, represent major areas of research necessary to enable the Outcomes consistent with ARMD's roles and capabilities. Each Research Theme includes one or more Technical Challenges, which are funded activities with specific objectives. These Technical Challenges serve as the basis for planning research activities and measuring performance.

ARMD's strategy will continue to focus on high-impact research investments that will enable the transformation of aviation to serve future needs, produce demonstrable benefits, and leverage technology advances outside of, as well as within, traditional aviation disciplines. Major technology foci include alternative fuels and electric or hybrid propulsion, low-sonic-boom supersonic flight, automation and autonomy, and technology convergence to develop transformative solutions, with the ultimate goal of enabling a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system.

A Letter to the Reader

The ability to safely move massive amounts of cargo and people through the air each day is a fundamental element of the nation's economy that impacts our daily lives in so many ways, both professional and personal. U.S. aviation generated $1.6 trillion in positive economy activity in 2014. U.S. airlines moved 797 million passengers and 18 million tons of freight in 2015. We and our nation depend on a globally connected, safe, and efficient air transportation system every day.

With more than a century of research as a foundation, NASA's best and brightest aeronautical innovators are working hard to improve aviation in ways that will see airplanes use less fuel, reduce emissions, and fly more quietly. At the same time, NASA is working with its government and industry partners to improve the efficiency and safety of the National Airspace System. This effort is taking place as global demand for air transportation is growing fast and other nations are conducting advanced aeronautics research in pursuit of developing their own aviation industries.

NASA's Aeronautics Research Mission Directorate in 2015 produced a Strategic Implementation Plan to address three overarching trends: growth in demand for high-speed mobility; sustainability and energy use, and technology convergence. The plan reflected stakeholder input and laid out a challenging vision to transform aviation by 2025 and beyond through concentration on six research thrusts detailed in the document. Since then, we have made considerable progress in enabling the vision that we established together. We've done this by aligning research projects and their objectives with the plan, while developing roadmaps that will guide our work for the next two decades and more – once again echoing stakeholder input at every step. New efforts were started as well, most notably NASA's New Aviation Horizons initiative that will see the return of X-plane projects to help accelerate implementation of new technologies by industry.

With so much new to share about where we were, where we are, and where we want to go, it was time to update this Strategic Implementation Plan – which was and still is a living document. Now as we move forward, we will put a premium on leveraging contributions from developments outside of NASA, and outside of aviation, to take advantage of burgeoning developments in revolutionary energy sources and propulsion concepts, automation and autonomy, machine intelligence, and new uses of airspace.

Aviation stands on the cusp of transformation that will bring new levels of economic and transportation opportunities. Introduction of new aircraft configurations that are more efficient by design than today's "tube and wing" air transports will enable new trend lines toward ultra-efficiency. These new designs will be matched with air traffic management technologies that enable the most direct and efficient routes possible. At the same time, the integration of unmanned aircraft systems (UAS), or “drones,” into the airspace represent just the tip of the iceberg for new “on-demand” aviation systems that will use highly autonomous flight controls and electric propulsion. These advances will enable “thin-haul” aircraft that can economically provide passenger and package transportation between small communities, as well as vertical lift aircraft that can offer air taxi and commuting services for intra-urban applications. Supersonic, and eventually hypersonic, flight is now on the horizon to complement and extend our global air transportation system. The thread that runs through this transformative future is technological leadership made possible by one of the most productive partnerships in U.S. history: NASA, industry and academia working together for the benefit of the U.S. economy and transportation system.

We will continue to reach out to the aviation community and beyond to make sure that we serve the public’s future needs for a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system. And when the time is right, we will offer another new version of this plan based on our accomplishments, lessons learned, and your input as well.

Together we stand on the cusp of the next era in aviation, and together we will make it happen.

Dr. Jaiwon Shin
Associate Administrator
NASA Aeronautics Research Mission Directorate

Introduction

In 2015, the NASA Aeronautics Research Mission Directorate (ARMD) published the initial edition of this Strategic Implementation Plan, 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.

This update reflects the work that has gone on to implement NASA's role for achieving the vision. Most notably, ARMD has developed a set of roadmaps for the six Strategic Thrusts established in the initial edition. The roadmaps, accessible through links at *www.nasa.gov/aeroresearch/strategy*, include updated statements of the Outcomes and Research Themes that will guide NASA's research efforts in aeronautics, as well as the capabilities and benefits that will accrue from the research. The portfolio of ARMD projects is currently being modified in accordance with these roadmaps, and ARMD has already launched new projects to support transformative objectives.

ARMD will continue to assess and update this document as we progress toward our goals, technologies mature, new technologies emerge, and the community's needs evolve.

Overview

Aviation is a critically important enterprise for the United States. It integrates the latest knowledge in advanced technologies developed over decades of concerted research. The mission of ARMD is to serve the future needs of civil aviation by conducting research into, and developing solutions for, the problems of flight. While the specific research problems have changed considerably since NASA's mission was written into the National Aeronautics and Space Act of 1958, aeronautical research remains as important now as it was in the early days of aviation.

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. It accounts for more than $1.6 trillion of U.S. economic activity each year and generates a positive trade balance – $82.5 billion in 2015. The aviation industry also supports nearly 11 million direct and indirect jobs, including more than one million high-quality manufacturing jobs.

Every individual feels the benefits of aviation. Nearly every product created and purchased today has been touched by aviation in some way. More than 18 million tons of freight were moved by air in the

United States in 2015, as well as 797 million passengers. Domestic and foreign air travelers spent more than $771 billion in the U.S. economy on hotels, rental cars and entertainment in 2014. In short, the U.S. aviation industry is critical to both economic and societal well-being.

Looking forward, global economic growth and urbanization are driving rapid increases in demand for aviation services, especially in the Asia-Pacific region and other high-growth areas. The International Air Transport Association (IATA) forecasts nearly a billion additional air passengers over the next six years, and demand for new aircraft and equipment is growing to keep pace. This expectation represents a substantial opportunity for U.S. economic growth and competitiveness, as well as providing a variety of benefits on a global scale.

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

Today, ARMD 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, alternative fuels, vehicle efficiency improvements, and reduction of noise and harmful emissions such as nitrogen oxides (NO_x). The future promises new roles for the aviation system. For example, just over the horizon lies the potential for UAS to serve myriad needs, from battling wildfires to retail distribution to delivering urgently needed medical supplies at remote locations.

Demand growth and change also pose long-term challenges in efficiency, safety, and energy use. New concepts and game-changing technologies will be needed to capture the opportunities of the future. Current technologies and evolutionary improvements will not keep pace with many of these growing challenges, nor will they enable the important and exciting new applications that lead to economic opportunity and societal benefit. For example, growth in demand for air service is forecasted to outstrip the ability to constrain energy use and carbon emissions.

Long-term aeronautics research provides the basis for new concepts that ultimately lead to industry innovation and societal benefit. ARMD focuses on research and technology development that is beyond the current grasp of industry, with emphasis on technologies to achieve societal 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.

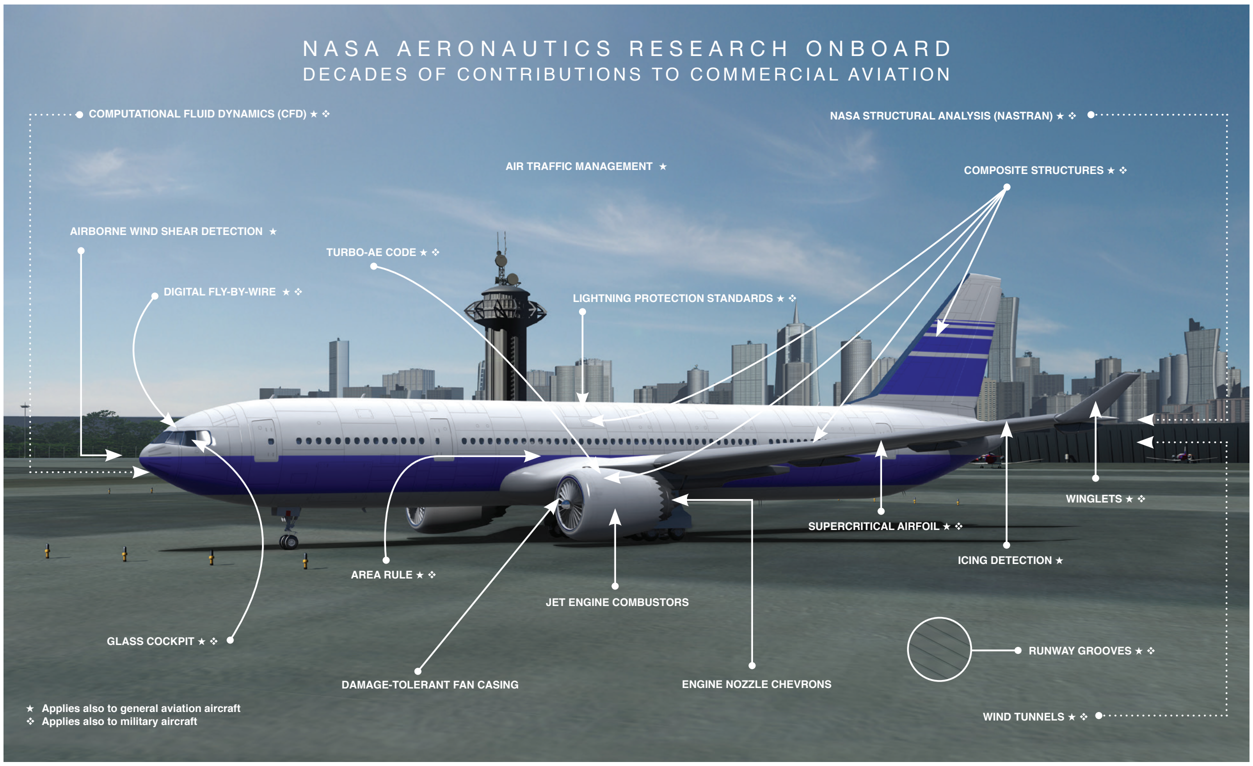

Figure 1. Applications of NASA Research Results in a Modern Commercial Aircraft

NASA Aeronautics Research Yesterday and Today

The year 2015 marks the 100th anniversary of the founding of NASA's predecessor, the National Advisory Committee for Aeronautics (NACA). Since that seminal event, aeronautics research has expanded from the fundamentals of flight to hypersonic air vehicles, from measuring the static performance of airfoils to understanding behavior of complex human-machine systems, and from wood-and-canvas structures to adaptive shape-changing materials.

NASA has a history of undertaking research and development (R&D) efforts that are outside the scale, risk, and payback criteria that govern commercial investments, with the purpose of proactively transitioning the research findings to the aviation community. NASA aeronautics research has delivered results producing substantial benefits for air transportation in the established ARMD focus areas of fundamental aeronautics, vehicle systems and configurations, air traffic management, and aviation safety. These results have transformed aviation to the benefit of the national economy, national defense, travelers, and shippers, as well as the global environment. As an example, Figure 1 illustrates major features of modern commercial aviation that have been made possible by ARMD research.

The history of NASA research begins with the establishment of the NACA 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, 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 NACA research focused on the physics of flight, with work involving wind-tunnel tests and flight tests of both models and full-scale aircraft. These tests and the development of theory addressing the aerodynamics of aircraft resulted in greatly increased aircraft speed, payload, and range. In the 1930s and 1940s, NACA developed airfoil shapes for wings and propellers that found their way into the designs of many U.S. aircraft of the time, including a number of important World War II-era aircraft such as the P-51 Mustang.

This period also saw the expansion of NACA's research into flying qualities as it began to examine aircraft behavior as a human-machine system. In 1941, a pioneering NACA report, "Requirements for Satisfactory Flying Qualities of an Airplane," by R. R. Gilruth, defined the first set of requirements for the handling characteristics of an aircraft; this work grew into the Cooper-Harper handling-qualities scale for aircraft, which is still in use today.

After World War II, the NACA began to work on the goal of supersonic flight, working closely with the Air Force and Bell Aircraft to design the first supersonic airplane – the X-1 experimental aircraft. This collaboration marked the NACA's first effort in dealing with the initial design, construction, and flight testing of a research airplane. At the same time, refinement of theory led to further aerodynamic improvements, such as development of the swept-wing concept by Robert T. Jones in 1945 and invention of the area rule concept by Richard Whitcomb in 1951. Development of the axial flow compressor in the 1950s, which became the basis for modern turbojet and turbofan engines, reflected further expansion of the NACA's research horizons.

Following the 1958 Space Act, which established NASA as the successor to the NACA, aeronautics research expanded to address flight beyond Earth's atmosphere. The X-15 research aircraft set an altitude record of 354,000 feet in 1963 and a record speed of Mach 6.7 in 1967. Research topics supporting this and other efforts included compressible flow aerodynamics, high-temperature materials, aircraft structures, and reaction controls. Notable achievements include development of the widely used NASA Structural Analysis (NASTRAN) tools in the 1960s, and initial development and application of computational fluid dynamics (CFD) in the 1970s.

In the 1970s and 1980s, research in supercritical airfoils, winglets, riblets, laminar flow control, and propulsion enabled further advances in performance, embodied in a vigorous flight demonstration program that included the Quiet Short-haul Research Aircraft, XV-15 tiltrotor research aircraft, and X-29 forward-swept-wing flight research aircraft. In this period, the scope of aeronautics research grew to include a number of important safety and performance enhancements such as digital fly-by-wire controls, "glass cockpits," airborne wind-shear detection, microwave landing systems, and head-up displays.

NASA's research contributed significantly to a transformation of commercial air transportation following the introduction of jet airliners beginning in the 1960s. Aircraft cruise speed increased 70% between 1960 and 1990, and energy efficiency doubled in terms of passenger miles per unit of fuel consumed. In the U.S. during the same period accidents per departure dropped by 90% and annual passenger miles flown increased tenfold.

Accomplishments since 1990 demonstrate not only further expansion of ARMD's 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. These accomplishments include the following, among many others:

- Development of FutureFlight Central full-scale airport operations simulator, simulations of the National Airspace System (NAS), and development of air traffic control and air traffic management tools.
- Exploration of air vehicle and propulsion concepts for energy efficient aircraft, including flight demonstrations of the Blended Wing Body (BWB) X-48B testbed and initiation of research into electric propulsion technology.
- Integration of human factors, guidance, displays, and intelligent flight controls into safety research.
- Further research in aircraft structures, composites, and high-temperature materials.
- Flight demonstration of techniques to shape sonic boom signatures to reduce sonic boom intensity.
- Further development of physics-based and multidisciplinary tools for aircraft design and analysis.

These and other efforts have made significant contributions to further reductions in accident rates worldwide, while U.S. passenger miles continued to grow by more than 50% since 1990 and aircraft became quieter and more energy efficient. Thanks in large measure to technology features attributable to ARMD research, commercial aircraft now entering service are 20% more energy efficient and have a noise footprint 60% smaller than the previous generation of aircraft.

This brief historical overview illustrates how ARMD research has produced large benefits by enabling transformative and far-reaching advances in aeronautics. Development of a sound knowledge base and advances in analysis and simulation have enabled the NACA and NASA to expand their aeronautical research perspectives within necessarily constrained resources. The history of NASA aeronautics also 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.

NASA Aeronautics Vision for the 21st Century

Global

Sustainable

Transformative

U.S. leadership for a new era of flight

6 Strategic Thrusts

- Safe, Efficient Growth in Global Operations
- Transition to Alternative Propulsion and Energy
- Innovation in Commercial Supersonic Aircraft
- Real-Time System-Wide Safety Assurance
- Ultra-Efficient Commercial Vehicles
- Assured Autonomy for Aviation Transformation

NASA Aeronautics Strategy

While past NASA aeronautics research has provided the U.S. aviation industry with transformative technologies, recent global trends call for a shift in focus beyond traditional research areas. In defining NASA's approach to meeting future aviation needs, the 2014 NASA Strategic Plan sets forth a bold objective for aeronautics research in Strategic Objective 2.1: *"Enable a revolutionary transformation for safe and sustainable U.S. and global aviation by advancing aeronautics research."* ARMD is responding with an equally bold vision embodied in this Strategic Implementation Plan.

ARMD's Strategic Planning Process

While ARMD research to date has made many important contributions to air transportation, analysis of global trends indicates that more and different research is needed to keep U.S. aviation safe, robust, and competitive, while also addressing global needs. The Strategic Implementation Plan provides a basis to guide research across a wide range of technology initiatives, helping to sustain the Nation's aeronautical leadership and supporting U.S. industry's ability to meet the needs of global aviation markets.

ARMD's vision, therefore, addresses the wider roles of aviation and aviation research organizations on a global scale. In evaluating those roles, ARMD recognizes that some research needs do not require NASA's expertise, and other research needs that are within ARMD's range of expertise are more properly served by other research organizations. ARMD's research strategy aims to operate productively within that collaborative global research environment, building on current leadership while enabling revolutionary technology advances.

Figure 2, depicts the hierarchy of elements that guides 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 High-Speed Mobility
- Mega-Driver 2: Affordability, Sustainability, and Energy Use
- Mega-Driver 3: Technology Convergence

ARMD's AERONAUTICAL RESEARCH TAXONOMY

STRATEGIC THRUSTS

ARMD Research is Organized into Six Strategic Thrusts

- Strategic Thrust 1: Safe, Efficient Growth in Global Operations
- Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft
- Strategic Thrust 3: Ultra-Efficient Commercial Vehicles
- Strategic Thrust 4: Transition to Alternative Propulsion and Energy
- Strategic Thrust 5: Real-Time System-Wide Safety Assurance
- Strategic Thrust 6: Assured Autonomy for Aviation Transformation

OUTCOMES

Outcomes are Defined for Each of Three Time Periods

Near-term: 2015-2025	Mid-term: 2025-2035	Far-term: Beyond 2035

RESEARCH THEMES

Long-Term Research Areas that will Enable the Outcomes

Most Outcomes encompass multiple Research Themes

TECHNICAL CHALLENGES

Specific Measurable Research Commitments within the Research Themes

Most Research Themes encompass several Technical Challenges (TCs); each ARMD program's projects list the TCs for which they are responsible. Visit www.nasa.gov/aeroresearch/programs

Figure 2. ARMD's Aeronautics Research Planning Framework

The *Mega-Drivers* are three overarching trends that will in large part shape the needs of aeronautical research in the coming years. For each Mega-Driver, ARMD has identified research that is both within the capabilities of ARMD's expertise and resources and beyond the capabilities of industry.

The *Strategic Thrusts* represent ARMD's overarching view of the community's response to the Mega-Drivers as they affect aviation. Taken together, the Strategic Thrusts constitute a vision for the future of aviation.

Outcomes supporting each Strategic Thrust signify the operational capability required to address the Strategic Thrusts. Because the Outcomes generally involve implementation of ARMD-developed technologies, they must rely on engagement and contributions from the broader aviation community.

Research Themes, which support the Outcomes, are defined as major areas of research necessary to enable the Outcomes consistent with ARMD's roles and capabilities. The Research Themes represent ARMD's long-term approach to pursuing research in particular technology areas. Each Research Theme addresses one or more Technical Challenges, which represent funded activities with specific objectives. The Technical Challenges serve as the basis for planning research activities and measuring performance.

Global Trends and Drivers

The three Mega-Drivers that emerged from the trend analysis — growth in air transportation demand, climate change, sustainability and growing energy use, and technology convergence — are critical vectors that shape major aeronautics research needs and structure ARMD's response. ARMD has established six Strategic Thrusts on the basis of an analysis of how these global trends will potentially determine the future of aviation.

Mega-Driver 1: Global Growth in Demand for High-Speed Mobility
A century-long trend of migration into cities across the globe is now generating urban growth at a level equivalent to seven Chicago-sized cities per year, and two thirds of the world's population will live in urban centers by 2050.[1] At the same time, there has been a trend toward higher speed transport. In 1990, buses, automobiles, and railroads accounted for 91% of the world's traffic volume, leaving only 9% to the high-speed transport modes of air and high-speed rail. But growth in urbanization and wealth by 2050 could increase the demand for high-speed transport to more than 40% of the world's traffic volume.[2]

For example, the economies of both China and India have been growing more than twice as fast in a 20-year span as did the U.S. economy during its most economically expansive 50-year period (1900- 1950). As a result, these countries are expected to account for half of the world's middle class population by 2050.[3] 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.

The International Air Transportation Association (IATA) projects that the number of air passengers world-wide will double by 2034.[4] To support that growth in demand, high-technology aircraft, powered by advanced renewable energy sources, will serve intercontinental traffic through a dozen global gateways, connecting at 50 to 75 regional U.S. hubs with air service to local airports.

This expanded and increasingly distributed demand for air travel will require increased high-technology manufacturing capacity. Rising demand will also have to be satisfied with efficient resource use to satisfy cost constraints and limit adverse environmental impacts.

1 United Nations Department of Economic and Social Affairs. World Urbanization Prospects: The 2014 Revision

2 Andreas Schafer et al. *Transportation in a Climate Constrained World*. MIT Press, 2009

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

4 International Air Transport Association, "Total Passengers Set to Double to 7 Billion by 2034," Press Release No. 55. 26 November 2015

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

Fuel is currently a significant driver of the cost of air transportation. According to IATA, 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 six between the 1990s and 2012. Fuel made up only 10% of total airline costs in 1995, but it increased to almost 30% by 2011. 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 to rise over the long-term, affecting affordability of air transportation and sustainability of current models of operation.

In terms of environmental impact, air transportation accounts for about 2% of the world's CO_2 emissions.[5] While this is a relatively small share, continued growth in air transportation could lead to larger effects. The industry has ambitious goals for reducing generation of CO_2 to enable sustainable growth and address climate change. These goals are to improve system-level fuel efficiency by 1.5% per year through 2020, achieve carbon-neutral growth beyond 2020, and by 2050 to reduce CO_2 emissions to 50% of 2005 levels.[6] Achieving these goals will require affordable renewable fuels and new low-carbon propulsion system concepts, as well as energy-efficient aircraft and operations.

Mega-Driver 3: Technology Convergence

Technology convergence, widely defined as the combination of two or more different technologies in a single device or product, has historically played a major role in technological innovation. 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.

Evolution of the internet and its uses provides an obvious, but far from unique, example. Past examples in aviation include convergence of analytical theory with computational capabilities and new materials that have made possible today's air vehicles. Another example is the various technologies that have converged in the Global Positioning System and its applications for navigation and air traffic control.

5 Data from United Nations Intergovernmental Panel on Climate Change, quoted by Air Transport Action Group a http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/. Accessed December 11, 2014

6 IATA Resolution on the Implementation of the Aviation "CNG2020 Strategy." June 2013

A current example is UAS, which have brought in new producers, users, technologies and missions, and raised new issues related to privacy, regulation, and airspace management. Today, rapid advances in energy, materials, manufacturing, and cyber-physical systems across a broad range of industries represent major examples of technology convergence that promise to transform aviation.

Biofuels and electric power as sources of energy for air vehicles will converge with technologies for energy storage and vehicle propulsion, as well as new infrastructure for energy distribution. Additionally, electric power allows efficient use of distributed propulsion, which can change the way aircraft are designed and controlled, leading to new vehicle configurations with enhanced performance, improved energy efficiency, and reduced emissions.

New materials, such as composites with tailored strength properties and ceramics for high-temperature applications, will continue to replace customary metal structures and components. With these materials come new producers and new means of manufacture. Convergence with advanced computational methods, robotics, and vehicle design concepts will lead to widespread use of 3-D printing, automated assembly, monolithic structures, shape-changing and multifunctional materials, and other new capabilities to reduce weight, lower manufacturing cost, enhance production flexibility, and improve vehicle performance.

Cyber-physical systems convergence is transforming operational concepts as increasingly intelligent systems enable highly networked systems-of-systems, remote operations, and on-demand systems and services. These advances have promoted innovations such as distributed self-services, exemplified by check-in kiosks at airports, on-demand shared automobiles, and internet streaming. Machine autonomy and robotics could lead to autonomous 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. Technology convergence may also affect the 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, although expanded telepresence, by increasing interactions among people separated by distance, might increase demand for aviation in ways that are hard to predict today – the historical impact of telephones and internet, increasing demand for travel by enabling connectivity to more people and over longer distances, are good examples of such an effect.

ARMD seeks to leverage rapid advancements in these 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.

Community Dialogue

In addition to strategic analyses and inputs from subject matter experts and senior stakeholders, ARMD's planning incorporates mechanisms for wide dialogue with the aviation community. To help identify important research areas and challenges of the future, ARMD has frequently engaged the aviation community to understand what its stakeholders believe are priority research areas. Regular discussions have engaged domestic and international partners and experts from industry, academia, and government. 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.

These sessions made it evident that the aviation community's highest priorities for research lie in safety, highly efficient aircraft, the evolution of the Next Generation Air Transportation System (NextGen), UAS access to the National Airspace System (NAS). More recently, community focus on on-demand aviation systems has increased as UAS have shown the potential for more profound changes to the aviation system. Facilitating advances in 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 indepth information that help support ARMD detailed research planning and partnership development. NASA has links to completed studies at https://www.nasa.gov/aeroresearch/strategy. 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.

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, provide access to a wide range of technologies beyond the traditional aeronautics portfolio, and facilitate technology transfer to more mature states of development and eventual implementation. Integrated technology demonstrations typically include selected industry or government partners who contribute their own funding or knowledge. 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 Federal Aviation Administration (FAA) to support that agency's decision making and to improve the performance of the NAS, as well as with the Department of Defense (DoD) and other government agencies to leverage technology investments. Industry partnerships allow rapid insertion of ARMD research results into air vehicles and subsystems, and 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 in various fields of study. 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 (IFAR).

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.

Jaiwon Shin, Associate Administrator for NASA ARMD, center, answers questions along with David Melcher, CEO of the Aerospace Industry Association (AIA), left, and former NASA Administrator Charles Bolden, right, during a press conference, Monday, Feb. 29, 2016 at Ronald Reagan Washington National Airport in Arlington, Va. Administrator Bolden announced the award of a contract for the preliminary design of a "low boom" flight demonstration aircraft as part of NASA's New Aviation Horizons initiative that was introduced in the agency's Fiscal Year 2017 budget. Image credit: NASA/Joel Kowsky

Strategic Response

ARMD has formulated six Strategic Thrusts to act as the link between its strategic vision and its research plans. In combination, these Strategic Thrusts respond to the needs of aviation to 2035 and beyond. The Strategic Thrusts are set forth as follows:

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 achieve much greater capacity and operational efficiency while maintaining or improving safety and other performance measures. ARMD will contribute specific research and technology to enable the continued development of NextGen and beyond. Projected growth in air travel will require a sustained focus on reducing safety risks to maintain acceptable levels of safety; to that end, ARMD will work with the FAA, the Commercial Aviation Safety Team (CAST), and others to perform research and to contribute technology addressing current and future safety risks. Similar ongoing international developments, such as the European Union's (EU's) Single European Sky Air Traffic Management Research (SESAR) effort, are being globally harmonized through the International Civil Aviation Organization (ICAO).

Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft

Development of efficient, cost-effective, and environmentally compatible commercial supersonic transports could not only be a game changer for transcontinental and intercontinental transportation, but could also provide an opportunity to maintain U.S. leadership in aviation systems, and to generate economic and societal benefits in a globally linked world. ARMD will perform selectively focused research and advance groundbreaking technologies to overcome the major environmental and efficiency barriers to market innovation in supersonic transport. Since overcoming these barriers will likely involve modifications to regulations and certification standards for supersonic flight, ARMD will conduct its research in cooperation with the FAA, ICAO, and other aviation regulatory agencies.

Strategic Thrust 3: Ultra-Efficient Commercial Vehicles

Large leaps in aircraft efficiency, coupled with reductions in noise and harmful emissions, are critical to the aviation community's roadmap for achieving greatly improved environmental sustainability. ARMD will develop critical technologies to enable future generations of subsonic fixed wing and vertical lift commercial aircraft that lessen environmental impacts while maintaining safety and improving operating economics. Toward this end, ARMD will coordinate with the DoD on dual-use technologies and concepts, and with the FAA's Continuous Lower Energy, Emissions and Noise (CLEEN) program on high Technology Readiness Level (TRL)[7] civil demonstrations.

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7 Technology Readiness Levels are used to identify the maturity of a technology, from TRL 1 through TRL 9. For example, TRL 1 indicates that information from basic scientific research is now taking technology from an idea to a practical application. TRL 9 describes when a technology has been fully incorporated into a larger system. NASA typically continues work through TRL 6, the point at which the technology is transferred to the community for further testing and/or manufacturing and implementation

Strategic Thrust 4: Transition to Alternative Propulsion and Energy

While high levels of aircraft and operational efficiency are required for the future, they will not be enough to produce absolute reductions in life cycle carbon emissions. Therefore, ARMD seeks first, to enable the use of alternative fuels, and second, to foster a fundamental shift to innovative aircraft propulsion systems that have the potential to produce very low levels of carbon emissions relative to the energy used. In support of this Strategic Thrust, ARMD will participate in implementing the Federal Alternative Jet Fuel R&D Strategy sponsored by the Aeronautics Science and Technology Subcommittee of the National Science and Technology Council.[8] ARMD will also coordinate with the DoD and FAA to perform research, leading to concepts and technology for alternative propulsive system architectures. Electrified Aircraft Propulsion is also an enabler for enhancing the efficiency of transport-class aircraft, improving the economics for small, short-range aircraft, and developing new on-demand aviation systems. NASA will work with both the established transport aircraft and emerging new aviation market communities to address key research issues associated with the safe introduction and scaling of electrified aircraft propulsion.

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

Commercial aviation is the safest mode of travel. This accomplishment is the result of decades of continuous improvement through proactive hazard management. With technology advances in sensors, networking, data mining, prognostics, and other analytic methods, the aviation community can now envision a day when safety will be achieved through recognition of safety risks as they develop in real time, allowing for implementation of mitigation strategies in time to prevent those risks from becoming safety issues. ARMD will lead research to support this vision and demonstrate the feasibility of integrated, system-wide safety assurance. Safety assurance will be essential to UAS and on-demand aviation systems as well as conventional operations; NASA will work with those communities as early adopters of this capability.

Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Ever-increasing levels of automation and autonomy are transforming aviation, 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 UAS in the NAS. Complementary methods will 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, and advanced metrics, models, and testbeds will enable the effective evaluation of autonomous systems in both laboratory and operational settings.

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8 Executive Office of the President, National Science and Technology Council. "Federal Alternative Jet Fuel R&D Strategy." June 2016.

Strategic Thrust Convergences

While the Strategic Thrusts define approaches to supporting the community's vision for the future of aviation, they are expected to evolve in response to changes in the Mega-Drivers and the emergence of new global trends. ARMD views these Strategic Thrusts as mutually supportive and, in some cases, converging vectors. For example, as technologies move to more integrated systems, Strategic Thrusts 1 (Safe, Efficient Growth in Global Operations), 5 (Real-Time System-Wide Safety Assurance), and 6 (Assured Autonomy for Aviation Transformation) may converge, enabling autonomic system concepts that increase capacity and efficiency while maintaining or enhancing system safety. Such convergence could enable systems that simultaneously achieve capabilities that have previously been considered as conflicting objectives subject to tradeoffs. Adaptive systems are a good example of such concepts. Similarly, convergence of Strategic Thrusts 3 (Ultra-Efficient Commercial Vehicles), and 4 (Transition to Alternative Propulsion and Energy) will allow selection of optimum combinations of technologies to enable environmentally sustainable aviation that will meet future demand. And convergence of Thrusts 3, 4, and 6 may enable a new class of small vertical lift vehicles that open new aviation markets.

Outcomes

Outcomes represent overarching aviation goals that are more than NASA alone can achieve. They are measurable goals for benefits to be achieved through joint efforts across the aviation community. ARMD research is meant to enable each Outcome, but others (FAA, industry, etc.) have key roles in achieving the Outcome and realizing the community's vision. In combination, the Outcomes for all six Strategic Thrusts articulate possibilities that span the interests and contributions of the entire aviation community.

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

- Near-term (2015-2025) 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 (2025-2035) 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 (>2035) 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 and ARMD's Role

Research Themes comprise major areas of research aligned to specific Outcomes. Unlike Outcomes and Strategic Thrusts, which represent aviation community goals that will be achieved through the community's joint efforts, the Research Themes are more focused. They define the roles that ARMD takes in conducting research that ultimately supports the Strategic Thrusts and Outcomes. In some cases, Research Themes reflect technology convergence that ARMD is seeking by combining rapidly advancing technologies from other fields with traditional ARMD strengths to achieve the Outcomes.

The Research Themes are pursued through programs and project organizations within the programs, and progress is reviewed on an annual basis. The research program offices define the Technical Challenges within each Research Theme and delegate them to the project organizations for execution. The project offices continually monitor their portfolios and develop plans that document the relevant Technical Challenges and how they will be addressed, as well as measures of progress and other programmatic information.

Four programs currently comprise ARMD's research activities:

- The Airspace Operations and Safety Program (AOSP) develops and explores fundamental concepts, algorithms, and technologies to safely increase throughput and efficiency of the National Airspace System. The AOSP also provides stewardship of Strategic Thrusts 1, and 5, ensuring that the Research Themes and Technical Challenges that enable the Outcomes are developed and maintained responsive to this Strategic Implementation Plan.
- The Advanced Air Vehicles Program (AAVP) 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 AAVP also provides stewardship of Strategic Thrusts 2, 3 and 4, ensuring that the Research Themes and Technical Challenges that enable the Outcomes are developed and maintained responsive to this Strategic Implementation Plan.
- The Integrated Aviation Systems Program (IASP) conducts research on promising concepts and technologies at an integrated system level, with a focus on flight research and demonstrations. IASP works with AOSP and AAVP to forecast and plan for needed flight research and demonstrations in support of all Strategic Thrusts.
- The Transformative Aeronautics Concepts Program (TACP) cultivates multidisciplinary, revolutionary concepts that transform aviation. TACP explores new solution paths that leverage the convergence of traditional aeronautics disciplines with other emerging technologies. TACP also provides stewardship of Strategic Thrust 6, ensuring that the Research Themes and Technical Challenges that enable the Outcomes are developed and maintained responsive to this Strategic Implementation Plan.

The section for each Strategic Thrust also identifies any major risks to achieving the community Outcomes that are targeted for mitigation by planned research. In addition, ARMD conducts crosscutting research in fundamental technologies that support multiple Strategic Thrusts and Research Themes. These crosscutting technologies are summarized starting on page 69.

ARMD will continue to explore new Research Themes as research progresses and community needs evolve. Similarly, Technical Challenges will evolve and eventually be replaced as they are achieved, community needs change, technologies advance, or new issues and technologies emerge.

In sum, ARMD's strategic planning process and dialogue with the aviation community have led to the definition of six Strategic Thrusts, supported by a hierarchy of Outcomes, Research Themes, and Technical Challenges. In this context, ARMD will continue its history of collaboration and partnerships with other members of the aviation community to evolve strategies, assess progress, and pursue a robust set of forward-looking research activities.

"The convergence of technologies we are seeing today, including automation, additive manufacturing, multi-functional structures, and an exciting array of other technologies, enables us to envision entirely new concepts in every aspect of the aviation enterprise. We will see a future with ubiquitous UAS, more highly efficient aircraft configurations, and entirely new propulsion systems. I believe we are on the verge of a new era of flight. And NASA has constructed an aeronautics strategy to help bring the benefits of this new era to the United States."

~ Dr. Jaiwon Shin
Associate Administrator, Aeronautics Research Mission Directorate

Members of a NASA-led research team pose in front of a trio of aircraft, which on February 22 concluded racking up enough air miles to circle the planet four times, all in the name of testing a new cockpit-based air traffic management tool. Image credit: Boeing

Strategic Thrust 1:
Safe, Efficient Growth in Global Operations

This section describes Strategic Thrust 1, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust. It includes the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

The Next Generation Air Transportation System (NextGen) is the Nation's plan for a modernized Air Traffic Management (ATM) system that will achieve much higher levels of operational capacity and efficiency while maintaining or improving safety and other performance measures. Strategic Thrust 1 responds to the NextGen plan and, further into the future, the Federal Aviation Administration's (FAA) vision to build on NextGen beyond 2025 to fully capture the opportunities enabled by cyber-physical systems research and other emerging technologies.[9] More efficient aircraft operations will reduce energy consumption, complementing Strategic Thrusts 3 and 4 in offering options for environmentally sustainable aviation.

Throughout the time periods from 2015 to 2035 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 National Airspace System (NAS) in the face of greater traffic volume and an increasing variety of vehicle types and missions.

Outcome for 2015-2025: Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1). The near-term will see enhanced domain efficiencies, supporting cost savings and reducing the environmental impact.

Outcome for 2025-2035: Full NextGen Integrated Terminal, En Route, Surface, and Arrivals/Departures Operations to Realize Trajectory-Based Operations (ATM+2). The 2025–2035 decade will see increased system efficiency, predictability, and reliability gains to further improve operations and support traffic growth, including full integration of UAS in the NAS.

Outcome for >2035: Beyond NextGen Dynamic Fully Autonomous Trajectory Services (ATM+3). Research exploration today will enable dynamic fully autonomous trajectory services, affording rapid adaptation to meet user demand or respond to system perturbations.

9 "The Future of the NAS." Federal Aviation Administration, June 2016

ARMD's Role

The technical focus of Strategic Thrust 1 is on future aviation system concepts, operations, and technologies. ARMD plays 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's 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 near-term (2015-2025) applications will focus on early improvements in NAS efficiency by implementing ongoing technology development in individual ATM domains and laying the foundation for revolutionary advances for both ATM+2 and ATM+3. Research includes modeling and simulation, tools to test Trajectory Based Operations (TBO) and NextGen concepts, and focus on safety issues such as loss of control and hazard awareness and detection.

Research aimed at the mid-term (2025-2035) will improve NAS efficiency and predictability by implementing gate-to-gate TBO, as well as continuing progress toward ATM+3 by providing enabling technologies, including: new ATM concepts, real-time predictive modeling and simulation tools integrated with safety assurance, and integrated safe autonomous UAS operations.

Exploratory research to support the far-term period (>2035) will focus on a revolutionary global aviation system with high levels of autonomy and safety prognostics that demonstrate game-changing efficiencies and enable new markets and vehicles.

ARMD also plans for continued research in engine and airframe icing to enable air vehicles to safely fly into various types of icing environments. This research will include validated computational and experimental icing simulations, as well as complementary on-board icing sensing radar to enable avoidance of icing conditions and to facilitate safe operation of current and future air vehicle concepts addressed in Strategic Thrusts 3 and 4.

Research Themes

The Research Themes described in Table 1, below, support the Outcomes associated with Strategic Thrust 1.

Table 1. Outcomes and Research Themes for Strategic Thrust 1

	STRATEGIC THRUST 1: SAFE, EFFICIENT GROWTH IN GLOBAL OPERATIONS		
	2015	2025	2035
Outcomes	Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1)	Full NextGen Integrated Terminal, En Route, Surface, and Arrivals/ Departures Operations to Realize Trajectory-based Operations (ATM+2)	Beyond NextGen Dynamic Fully Autonomous Trajectory Services (ATM+3)
Research Themes	**Advanced Operational Concepts, Technologies, and Automation** Research and development of operational efficiency incorporating proactive safety risk management in operational domains **Safety Management for Emergent Risks** Research and development of prognostic safety risk management solutions and concepts for emergent risks **Integrated Modeling, Simulation, and Testing** Development, validation, and application of advanced modeling, simulation, and testing capabilities to assess integrated, end-to-end NextGen trajectory based operations functionality, as well as seamless UAS operations and other future aviation system concepts and architectures **Airspace Operations Performance Enablers** Advanced research to develop performance requirements and guidelines for enablers, including operational guidelines and standards for new vehicles, secure infrastructure requirements, and assuring reliability of safety critical software for integrated, end-to-end global airspace		

Major Outcome Risks Addressed by Planned Research

Planned research addresses two major risks to enabling safe, efficient growth of global operations:

- Without further research, limitations of high-fidelity modeling and testing capabilities for advanced solutions to capacity, efficiency, and safety issues may impede the development and implementation of solutions, and hence retard growth in global operations.
- Projected demand for increased traffic volume and variety of operations beyond the near-term will not be met without transformational solutions for ATM and safety assurance.

Mechanical technician Dan Pitts prepares a nine percent scale model of Lockheed Martin's Quiet Supersonic Technology (QueSST) X-plane preliminary design for its first high-speed wind tunnel tests at NASA's Glenn Research Center. Image credit: NASA

Strategic Thrust 2:

Innovation in Commercial Supersonic Aircraft

This section describes Strategic Thrust 2, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust. It includes the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

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

Environmental barriers include the adverse impacts of sonic boom noise, airport community noise, high-altitude emissions, and high energy consumption. Successful supersonic commercial aircraft must overcome the current prohibition against supersonic overland flight imposed to prevent public annoyance from sonic boom, and they must contend with or avoid operationally inefficient subsonic flight segments required for integration with existing air traffic. Additionally, high fuel consumption and cost due to inefficient airframe aerodynamics and propulsion system performance result in poor operating efficiency and economics. 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.

Outcome for 2015-2025: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise. Over the next decade, research will focus on enabling the replacement of rules prohibiting overland supersonic flight with noise certification standards for en route supersonic noise, opening the market for new supersonic aircraft.

Outcome for 2025-2035: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports. A new market for fast point-to-point transportation will be served by environmentally compatible small supersonic aircraft, creating new business and job growth opportunities.

Outcome >2035: Increased Mission Utility and Commercial Market Growth of Supersonic Transport Fleet. A variety of air transportation markets will be served by supersonic aircraft with capacities as large as 200 passengers, offering rapid travel with competitive economics and reduced environmental impact.

ARMD's Role

The viability of commercial supersonic service depends on permissible supersonic flight 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 supersonic transports.

Since commercial overland supersonic flight is currently prohibited, ARMD's strategy for the near-term (2015-2025) is to focus on enabling establishment of a standard for allowable sonic boom. Because international routes comprise a major share of the potential market for supersonic service, ARMD will work with the international standards community to define sonic boom levels based on scientifically valid data on community response to low noise supersonic overflight. 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.

ARMD research supporting the mid-term (2025-2035) Outcome objectives will focus on technologies enabling the first and second embodiments of a new generation of supersonic transports, with emphasis on acceptable community and en route noise and high altitude emissions, as well as ATM technologies and procedures for efficient supersonic and terminal operations.

Research objectives beyond 2035 will focus on technologies enabling supersonic transports that are competitive in the airline market, with emphasis on high efficiency and light weight for improved economics, as well as ATM technologies for efficient supersonic airline operations.

Table 2, presents the targeted capability metrics for supersonic air vehicles in 2025-2035 and beyond 2035.

Table 2. Targeted Supersonic Transport Capability Metrics

VEHICLE CAPABILITIES	VEHICLE GENERATION	
	MID-TERM 2025-2035	FAR-TERM BEYOND 2035
Operating Economics	Business aircraft economics	Airline economics
Cruise Speed	Mach 1.6 to 1.8	Mach 1.3 to 1.6 overland, higher over water
Range	4,000 n.mi.	4,000 to 5,500 n.mi.
Passengers	6 to 90	100 to 200
Sonic Boom Noise	70 to 75 PLdB	65 to 70 PLdB
Airport Noise	Airport noise: ICAO Ch. 14, with margin	Airport noise: 15 EPNdB below Ch. 14
Cruise NO_x Emissions	<10 grams per kg fuel+	<5 grams per kg fuel (plus reduced particulates and H2O vapor)

Research Themes

The Research Themes described in Table 3, below, support the Outcomes associated with Strategic Thrust 2.

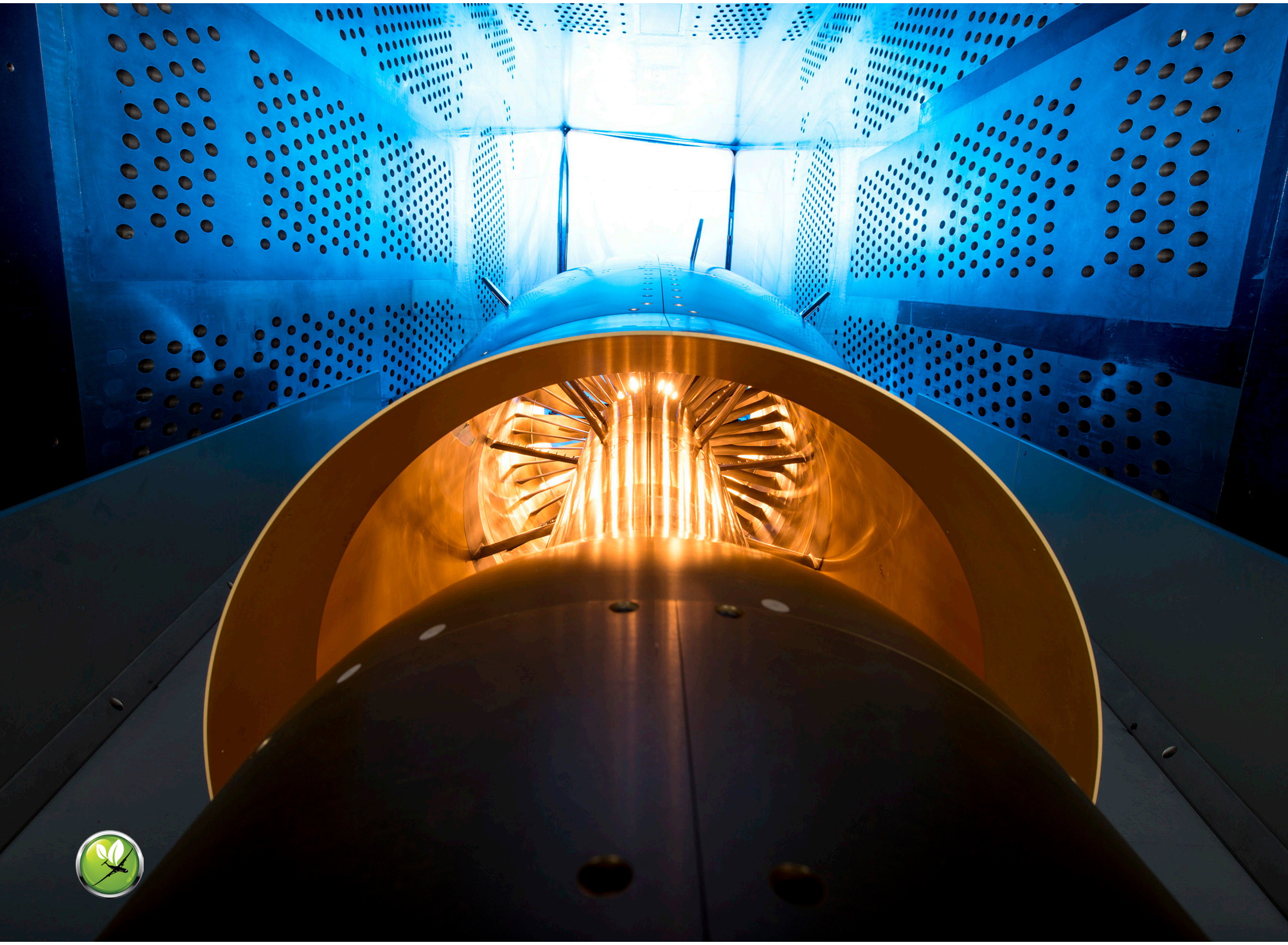
Table 3. Outcomes and Research Themes for Strategic Thrust 2

STRATEGIC THRUST 2: INNOVATION IN COMMERCIAL SUPERSONIC AIRCRAFT			
	2015	2025	2035
Outcomes	Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	*Increased Mission Utility and Commercial Market Growth of Supersonic Transport Fleet*
Research Themes	**Elimination of Environmental Barriers to Commercial Supersonic Aircraft** Understanding and measuring community response to supersonic en route noise, minimizing the airport community noise impact of supersonic 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; sonic boom mitigation technology **Modeling & Simulation, Test Capability** Integrated, physics bases models for aircraft design and analysis, quiet wind tunnel and acoustic test facilities **Efficient Supersonic Flight Operations** Flight systems and cockpit displays for minimized impact of en route supersonic noise, operations for supersonic en route noise impact mitigation, airspace integration for maximum supersonic operational efficiency		

Major Outcome Risks Addressed by Planned Research

The critical risk addressed by the research plan for this Strategic Thrust is the capacity of emerging supersonic aircraft technologies to support the elimination of today's prohibition against overland supersonic flight through the reduction of sonic boom to a publicly acceptable level.

This is an artist's concept of a possible Low Boom Flight Demonstration Quiet Supersonic Transport (QueSST) X-plane design. The award of a preliminary design contract is the first step towards the possible return of supersonic passenger travel – but this time quieter and more affordable. Image credit: Lockheed Martin



Inside the 8-x 6-foot wind tunnel at NASA's Glenn Research Center, engineers recently used a new fan and inlet design to test a concept called Boundary Layer Ingestion, or BLI. This is where air that has been slowed down by passing over an aircraft surface enters the engine and then is re-accelerated. The overall effect is less drag for the aircraft and a reduction of four to eight percent in fuel burn compared to today's advanced aircraft. Image credit: NASA/Rami Daud (Alcyon Technical Services)

Strategic Thrust 3

Ultra-Efficient Commercial Vehicles

This section describes Strategic Thrust 3, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust. It includes the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

This Strategic Thrust aims primarily at the two generations of air vehicles that will follow those now being developed. The community vision for this Strategic Thrust is based largely on improved environmental performance to address growing public concern about environmental sustainability, as well as enabling increased efficiency and flexibility of future air vehicles to achieve better economics and reduced fuel use. These future vehicles will support worldwide growth in aviation while facilitating public acceptance by virtue of lower noise and diminished impact on local air quality and climate change.

The 2016 National Academies report on commercial aircraft propulsion and energy systems research sets forth some of the parameters guiding the research in this Strategic Thrust.[10] The report focused on propulsion and energy technologies for reducing carbon emissions from large commercial aircraft, and it identified high-priority research projects divided among four key topics related to propulsion and energy technologies. The first two key topics, advances in aircraft–propulsion integration and improvements in gas turbine engines, are particularly applicable to this Strategic Thrust.

The Outcomes focus on increasing levels of efficiency and environmental compatibility, reflecting community views on what could be achieved, as well as the vehicle capabilities necessary to meet market requirements and civil air transportation needs in the future. Separate Outcomes are defined for subsonic transport and vertical lift vehicles.

ARMD research supporting Strategic Thrust 3 encompasses two separate vehicle families related to two segments of the aviation community: subsonic transports (Strategic Thrust 3a) and civil aircraft that incorporate vertical lift capability (Strategic Thrust 3b).

10 National Academies of Sciences, Engineering, and Medicine, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC: The National Academies Press, 2016

Strategic Thrust 3a

Subsonic Transport

Community's Vision

Although innovative concepts hold the promise of transforming air transportation in future decades, the aviation community expects that long-haul subsonic transports will provide the bulk of global and domestic air transportation through at least the near- and mid-term. Sustainable growth to meet the continually growing demand for air transportation during these decades will call for safe, economical, energy-efficient and quiet community-friendly transport aircraft with the payload, speed, and range performance demanded by the market.

These attributes will require that the community accelerate performance improvements while continuing to reduce development, manufacturing, and operational costs without compromising safety. Community performance goals for subsonic transports include specific levels of reduction in energy consumption, emissions of nitrogen oxides (NO_x), and noise. These goals support reductions in carbon emissions expressed in an IATA resolution that calls for a 1.5% average annual fuel efficiency improvement between 2010 and 2020, carbon neutral growth from 2020 onward, and a reduction of 50% in net emissions by 2050 compared to 2005 levels.[11] The performance goals also support meeting and exceeding projected noise and NO_x standards, such as those recommended by the International Civil Aviation Organization (ICAO).[12]

Figure 3, from the website of the commercial aviation industry Air Transport Action Group (ATAG),[13] illustrates the community view of how carbon neutrality will be achieved through a combination of technology innovation, operational improvements, infrastructure efficiencies, and economic measures to incentivize emission reductions.

11 International Air Transport Association. IATA Resolution on the Implementation of the Aviation "CNG2020 Strategy." June 2013

12 International Civil Aviation Organization. "Developments in Civil Aviation and the Environment," ICAO Working Paper A38-WP/25. July 18, 2013

13 http://aviationbenefits.org/environmental-efficiency/our-climate-plan/. Accessed September 25, 2014

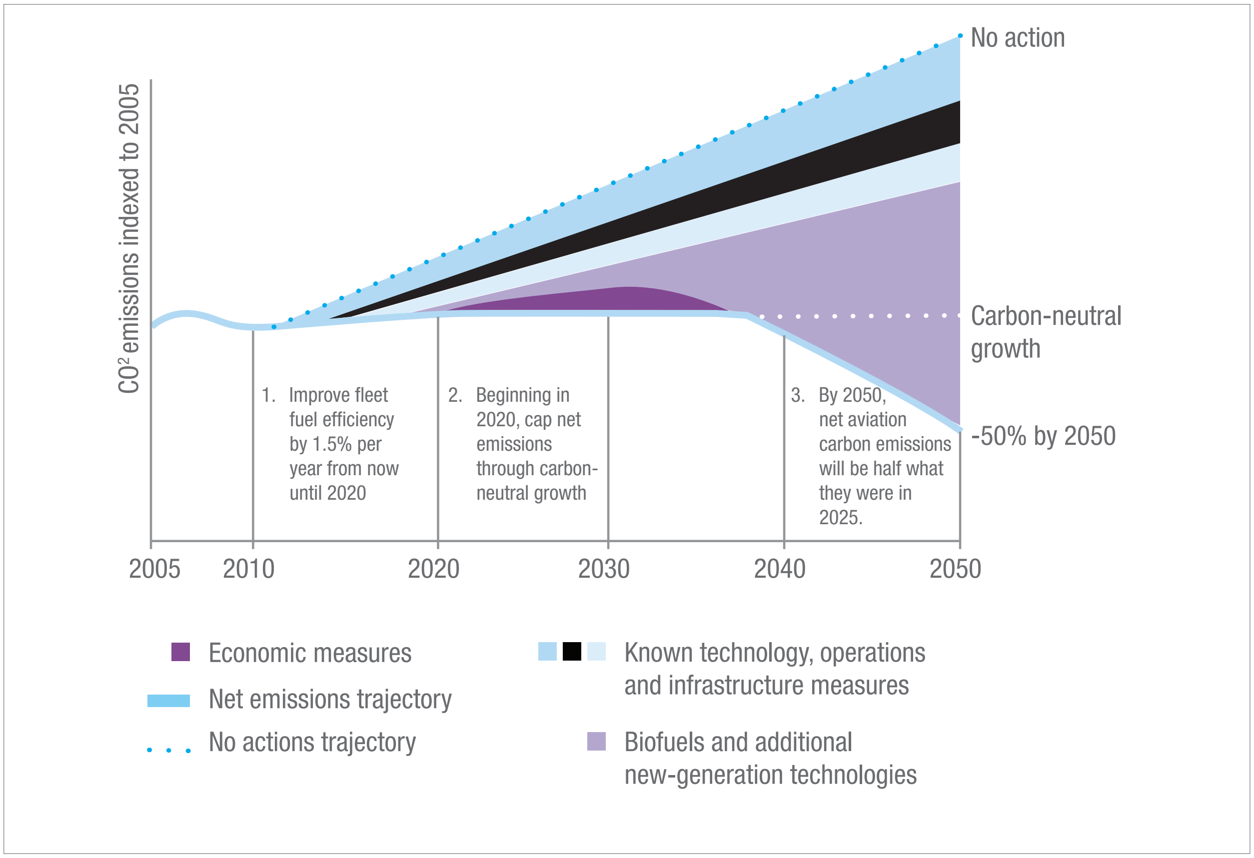


Figure 3. Aeronautics Community Vision for Achieving Carbon Neutrality.

Outcome for 2015-2025: Aircraft meet economic and environmental demands of airlines and the public, and are on a defined path to fleet-level carbon neutral growth. In the near-term, mature technology will enable new transport-class aircraft to be designed, developed, and produced that achieve continued improvement of fleet efficiency by 1.5 percent per year.

Outcome for 2025-2035: Aircraft meet economic demands of airlines and the public with revolutionary improvements in community noise and energy efficiency to achieve fleet-level carbon neutral growth relative to 2005. In the mid-term, mature technology and advances in technology and design approaches will enable new configuration concepts to be designed, developed, and produced that achieve accelerated improvement of fleet efficiency beyond 2 percent per year.

Outcome for >2035: Aircraft meet economic demands of airlines and the public with transforming capabilities in community noise and energy efficiency enabling a 50 percent reduction in fleet-level carbon output relative to 2005. In the far-term, mature technology and new configuration concepts will enable transport-class aircraft to be designed, developed, and produced that achieve a 50 percent reduction of fleet-level carbon output by 2050 compared to 2005 levels and produce less than half the perceived noise compared to 2005 best in class. In this timeframe, low-carbon propulsion, as defined in Strategic Thrust 4, will appear in transport-class vehicles, making possible new levels of reduced production of CO_2 and harmful emissions.

ARMD's Role

ARMD air vehicle research is segmented into technologies for near-term (2015-2025), mid-term, (2025-2035) and far-term (>2035) generations of vehicles with increasing efficiency and environmental performance. Notional Vision aircraft configurations and enabling technologies, defined by ARMD in collaboration with industry and academia, allow ARMD and the aviation community to estimate integrated aircraft performance that could meet the community's performance goals during these timeframes — 2015 to 2025, 2025 to 2035, and beyond 2035 — with technologies that could be available during those periods.

The vision vehicle concepts are designated as progressively more capable designs. ARMD's approach is to help enable the rapid evolution of current and emerging revolutionary technologies in the near-term while pioneering future technologies and vehicle concepts that will enable transformational improvements in efficiency, noise, and emissions. Throughout, ARMD will continue to support fundamental improvements in vehicle modeling, design, test, and evaluation, as well as advances in aerodynamics and aeromechanics, combustion, and certification and use of composites and other advanced materials.

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 serve as "technology collectors," enabling assessments of the technologies in terms of their impact on attributes of a vehicle design under various scenarios and constraints, as well as their dependencies on other technologies. The conceptual designs also enable comparisons of performance, technical risk, and other attributes of advanced vehicle concepts. In addition, the research will ensure that the safety implications of advanced technologies and concepts are identified and considered in the development process.

The concepts, technologies, and methods with the highest potential impact are prioritized for further R&D. ARMD will explore and develop these game-changing technologies, and then prove the practicality of revolutionary and transformational concepts and integrated technologies via large-scale demonstrations to facilitate technology transfer into commercial products. In addition, ARMD conducts crosscutting research, such as advanced computational methods and innovative structural materials, that supports the broad range of vehicle concepts. The result is a base of evolving research and technology for the next generations of vehicles that will be developed and produced by industry. ARMD also partners with industry and the FAA for research in specific areas for early transition to the immediate near-term aircraft. In addition, ARMD cooperates with industry and academia in exploring concepts and technologies for mid- and far-term aircraft.

Table 4, presents the targeted metrics for the projected subsonic transport vehicles relative to current performance. The table shows target dates for demonstrating the technologies (TRL 5-6) leading to first application in a commercial aircraft.

Table 4. NASA Targeted Improvements in Subsonic Transport System-level Metrics

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near-term 2015-2025	Mid-term 2025-2035	Far-term Beyond 2035
Noise (cumulative below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NO_x Emissions (below CAEP 6)	70 - 75%	80%	>80%
Cruise NO_x Emissions (relative to 2005 best in class)	65 - 70%	80%	>80%
Aircraft Fuel/Energy Consumption (relative to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

Research Themes

The Research Themes described in Table 5, below, support the Outcomes associated with Strategic Thrust 3a for subsonic transport aircraft.

Table 5. Outcomes and Research Themes for Strategic Thrust 3a – Subsonic Transport

STRATEGIC THRUST 3: ULTRA-EFFICIENT COMMERCIAL VEHICLES – SUBSONIC TRANSPORT			
	2015	2025	2035
Outcomes	Aircraft meet economic and environmental demands of airlines and the public, and are on a defined path to fleet-level carbon neutral growth	Aircraft meet economic demands of airlines and the public with revolutionary improvements in community noise and energy efficiency to achieve fleet-level carbon neutral growth relative to 2005	Aircraft meet economic demands of airlines and the public with transforming capabilities in community noise and energy efficiency enabling a 50 percent reduction in fleet-level carbon output relative to 2005
Research Themes	**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 **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 **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 airframe-propulsion integration **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 Risks Addressed by Planned Research

Planned ARMD research for subsonic transport vehicles addresses two major risks to achieving the desired Outcomes for Strategic Thrust 3:

- Evolutionary technology improvements alone will be inadequate to meet energy efficiency and environmental constraints while serving future demand for aviation services.
- Without flight demonstration of advanced concepts and technologies, industry will not take the high risk of commercial development, and full energy efficiency and noise performance goals will not be met. This concern is particularly true for advanced alternative vehicle configurations needed to meet the mid- and far-term goals

Strategic Thrust 3b

Vertical Lift

Community's Vision

Community goals for vertical lift aircraft reflect a need for improved performance on a wide variety of missions while enhancing safety and overcoming the historic barriers of speed, efficiency, operating cost, and environmental considerations – particularly noise. In the near-term, technology will continue to improve the safety, noise level, and other attributes of current and emerging vertical lift vehicles. Improvements in operational suitability of vertical lift configurations will enable growth in existing applications, as well as new markets. Further into the future, innovative direct lift and other configurations will further expand the markets for vertical lift, as well as the consequent economic and public good benefits of point-to-point origin-to-destination air transportation. Many UAS applications expected to flourish in the coming decades will call for vertical lift, as illustrated by proposed concepts for retail delivery, search and rescue, exploration, and other missions. On-demand aviation applications, including nascent air taxi and thin haul transportation markets will also take advantage of advanced vertical lift capabilities. Realizing the potential of these markets will call for meeting aggressive goals in efficiency, noise reduction, and expansion of the speed envelope of vertical lift aircraft. NASA will also be expanding its traditional vertical lift partnerships to new entrants in the UAS and on-demand aviation communities.

Outcome for 2015-2025: Increased capability of vertical lift configurations that promote economic benefits and improve accessibility for new and current markets. Near-term improvements to performance, efficiency and noise will enable reduction in direct operating cost, increased accessibility to sensitive areas, and growth in new and current markets.

Outcome for 2025-2035: New vertical lift configurations and technologies introduced that enable new markets, increase mobility, improve accessibility, and reduce environmental impact. In the mid-term, advances in technology and by unique technologies and configurations will enable new vehicle concepts, markets, and applications. Mobility and accessibility will be increased through reliable, safe, and quieter operation in a wider range of locations and conditions.

Outcome for >2035: Vertical lift vehicles of all sizes used for widespread transportation and services, and improved mobility and accessibility, with economic benefits and low environmental impact. In the far-term, advances in technology and design approaches will enable economic, environmental, and public benefits through a spectrum of vertical lift vehicle configurations that provide services, transportation, and unique mission capability.

ARMD's Role

ARMD near-term (2015-2025) research for vertical lift (including rotary wing) vehicles aims at key capabilities and technologies that directly benefit vertical lift for industry and government. These include validated tools for multi-discipline vehicle design, analysis and optimization; modeling noise from the entire vehicle; and conducting trade studies, as well as technologies for pilot workload reduction, improved turbomachinery and power-transmission efficiency, and lower drag for increased speed, range, and payload and lower fuel burn.

Mid-term (2025-2035) research focuses on key technologies that will enable U.S. industry to expand the global vertical lift market while setting new standards in noise, performance, and reliability, These include predicting noise and the human response to it, high-fidelity computational algorithms for full configuration simulations, efficient alternative propulsion options, and on-board systems to enhance safe operations in icing conditions, degraded visual environment, and confined or urban areas.

Beyond 2035, vertical lift research is aimed at capabilities and technologies that will eliminate barriers for clean, efficient, quiet autonomous vehicles operating in urban and isolated environments. These include prognostic condition-based maintenance systems, integration of lift and propulsion systems, methods for real-time low-noise operations, and advanced experimental methods for ground and flight test validation of innovative vehicle configurations.

Research Themes

The Research Themes described below support the Outcomes associated with Strategic Thrust 3b for vertical lift vehicles.

Table 6. Outcomes and Research Themes for Strategic Thrust 3b – Vertical Lift

<table>
<tr><th colspan="4">STRATEGIC THRUST 3: ULTRA-EFFICIENT COMMERCIAL VEHICLES – VERTICAL LIFT</th></tr>
<tr><td colspan="2">2015</td><td>2025</td><td>2035</td></tr>
<tr><td>Outcomes</td><td>Increased capability of vertical lift configurations that promote economic benefits and improve accessibility for new and current markets.</td><td>New vertical lift configurations and technologies introduced that enable new markets, increase mobility, improve accessibility, and reduce environmental impact</td><td>Vertical lift vehicles of all sizes used for widespread transportation and services, improved mobility and accessibility, with economic benefits and low environmental impact</td></tr>
<tr><td>Research Themes</td><td colspan="3">Clean and Efficient Propulsion
Research and development advancing the efficiency of propulsion systems

Expanded 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, Accessibility
Research and development of technologies and capabilities that improve passenger and public safety during operations.

Research and development of technologies that improve vehicle dynamic response
Research and development of technologies, configurations and operational concepts that improve access to transportation and services.

ModSim & Test Capability
Research and development of technologies and capabilities that improve passenger and public safety during operations.</td></tr>
</table>

Major Outcome Risks Addressed by Planned Research

Planned ARMD research for vertical lift vehicles addresses the same two major risks to achieving the desired Outcomes for Strategic Thrust 3: as those described for subsonic transport aircraft.

- Evolutionary technology improvements alone will be inadequate to meet energy efficiency and environmental constraints while serving future demand for aviation services.
- Without flight demonstration of advanced concepts and technologies, industry will not take the high risk of commercial development, and full energy efficiency and noise performance goals will not be met. This concern is particularly true for advanced alternative vehicle configurations needed to meet the mid- and far-term goals.

Before the first electric propulsion X-planes fly, such as the X-57, researchers at NASA's Armstrong Flight Research are using a unique test stand to understand the intricacies of how electric motor systems work. The goal of using this technology is to burn less fuel, while reducing emissions and noise. In this photo, Yohan Lin, Airvolt integration lead, prepares the electric propulsion test stand. Image credit: NASA/Lauren Hughes

Strategic Thrust 4:

Transition to Alternative Propulsion and Energy

This section describes Strategic Thrust 4, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust. It includes the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

This Strategic Thrust addresses both the established large transport and emerging small aircraft markets with a long-term vision in which the needs of these two communities come together. Key large transport aircraft needs are identified in the findings of the National Academies report on commercial aircraft propulsion and energy systems cited in the section on Strategic Thrust 3. The report focused on propulsion and energy technologies for reducing carbon emissions from large commercial aircraft (targeting technologies available to enter service in the fleet 10-30 years out), and it identified four key topics related to propulsion and energy technologies. These topics are: advances in aircraft–propulsion integration, improvements in gas turbine engines, development of turboelectric propulsion systems, and advances in sustainable alternative jet fuels. In addition, electrified aircraft propulsion has been identified as a key enabler for low-cost, environmental-friendly, small aircraft for new emerging markets. Key technology needs for small aircraft for these new markets have been gathered through interactions with industry and a series of On-Demand Mobility and Transformative Flight Workshops.

Community's Vision

This Strategic Thrust will help to achieve environmental sustainability by enabling absolute reductions in carbon emissions. The air traffic efficiency sought under Strategic Thrust 1 and the vehicle efficiencies sought under Strategic Thrust 3 will greatly reduce the impact of aviation on climate change. However, those efforts alone will not achieve the community's goal of enabling aviation growth while reducing net emissions 50% by 2050 compared to 2005 levels. As shown in a position paper prepared by the global aviation industry and illustrated in Figure 3, the community expects this goal to be achieved through a combination of more efficient operations, improved vehicle fuel efficiency and, in the longer term, new propulsion concepts and biofuels.

Strategic Thrust 4 will, therefore, complement the research on improved air vehicles and efficiency of airspace use by focusing on two transformational capabilities: first, the use of low life-cycle carbon fuels for conventional gas turbine engines and their future derivatives, and second, new propulsion systems that use alternative jet fuels and, possibly, other energy sources.

The aviation community has high confidence that low-life-cycle carbon fuels for conventional engines can be successfully implemented for use by commercial aviation, and that these will provide significant environmental benefit. There is less certainty that alternative propulsion systems (such as electrified aircraft propulsion systems) using other than petroleum-based energy sources can be successfully developed. However, advances in renewable energy and energy systems outside of the aviation sector provide sufficient optimism to pursue these concepts. Successful introduction of non-petroleum-based concepts would provide radically increased environmental benefits.

Electrified aircraft propulsion concepts, employing a combination of conventional and electric power, represent one promising candidate approach for low-carbon propulsion in 2025 and beyond. These concepts employ the best power source or combination of sources to provide the power needed in various flight conditions, and they offer flexible options for airframe designers to reduce drag or achieve other desired attributes. ARMD has conducted system studies and drafted research plans for this promising approach, and more work is ongoing to understand the full range of options, benefits, and hurdles to implementation.

The initial target will be to implement the high-confidence and significant-payoff option of reduced-emission drop-in alternative fuels for conventional engines, since this approach provides the fastest and lowest-risk path to improvements. As this incremental option reaches its maximum potential, fulfilling the community targets for carbon neutrality will require more attention to higher-payoff alternatives by exploring the full range of fuel and propulsion system options.

Outcome for 2015-2025: Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems. Over the next decade, sustainable alternative drop-in fuels will begin to make a difference in fleet carbon reduction beyond that from efficiency gains, and markets will begin to open for electrified small aircraft. At the same time, research will continue to develop scientific understanding of combustion emissions and environmental impact in order to inform decisions on emissions standards.

Outcome for 2025-2035: Initial Introduction of Alternative Propulsion Systems. In this decade, advanced propulsion systems with optimized use of sustainable drop-in fuels that are economically produced in sufficient quantities will substantially reduce fleet carbon emissions, and certified small-aircraft fleets enabled by electrified aircraft propulsion will provide new mobility options. The decade may also see initial application of electrified aircraft propulsion on large aircraft.

Outcome for >2035: Introduction of Alternative Propulsion Systems to Aircraft of All Sizes. Beyond 2035, sustainable alternative drop-in fuel use is expected to be the norm for advanced, optimized gas turbines and alternative propulsion systems. The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.

ARMD's Role

ARMD will help to achieve low-carbon propulsion through research in two areas. First, in partnership with the aviation community, is the development of data and analyses to support the use of a suite of certified, commercially available alternative drop-in jet fuels that will lower the total carbon footprint of traditional gas turbine engines and their future derivatives. Second is to explore the possibility of achieving very low or zero carbon emissions through new propulsion systems that leverage the properties of alternative drop-in and non-drop-in jet fuels and renewable energy sources.

In the near term (2015-2025), ARMD will continue working with current collaborators and partners to complete ongoing efforts to lower the emissions of aircraft that use conventional propulsion systems. This effort will include characterization of emissions of alternative jet fuels. In addition, ARMD will engage with the community to explore initial applications of alternative propulsion systems for small aircraft that may open new aviation markets, and future options for low-carbon transport-class propulsion.

For the mid term (2025-2035), ARMD will take the lead in identifying, evaluating, and down-selecting alternative propulsion systems. Electrified aircraft propulsion represents one promising candidate approach that ARMD has studied, but more work is needed to assess the full range of options, their benefits and risks, and hurdles to implementation. Throughout the process ARMD will conduct comparative analyses and selective testing of potential technology advances offering transformative propulsion architectures that might enable new mobility missions or further reduce the adverse environmental impacts of aviation. ARMD will also advance propulsion systems with optimized use of sustainable drop-in fuels that are economically produced in sufficient quantities to substantially reduce fleet carbon emissions.

In the far term (>2035), ARMD will participate in testing and demonstration of full-scale propulsion systems and fuels deemed most effective in the mid-term analyses. ARMD will then support the implementation of alternative systems and fuels for use by the full range of aircraft, including large transport aircraft that account for where the most energy is used and, therefore, where the largest impact on performance lies.

Research Themes

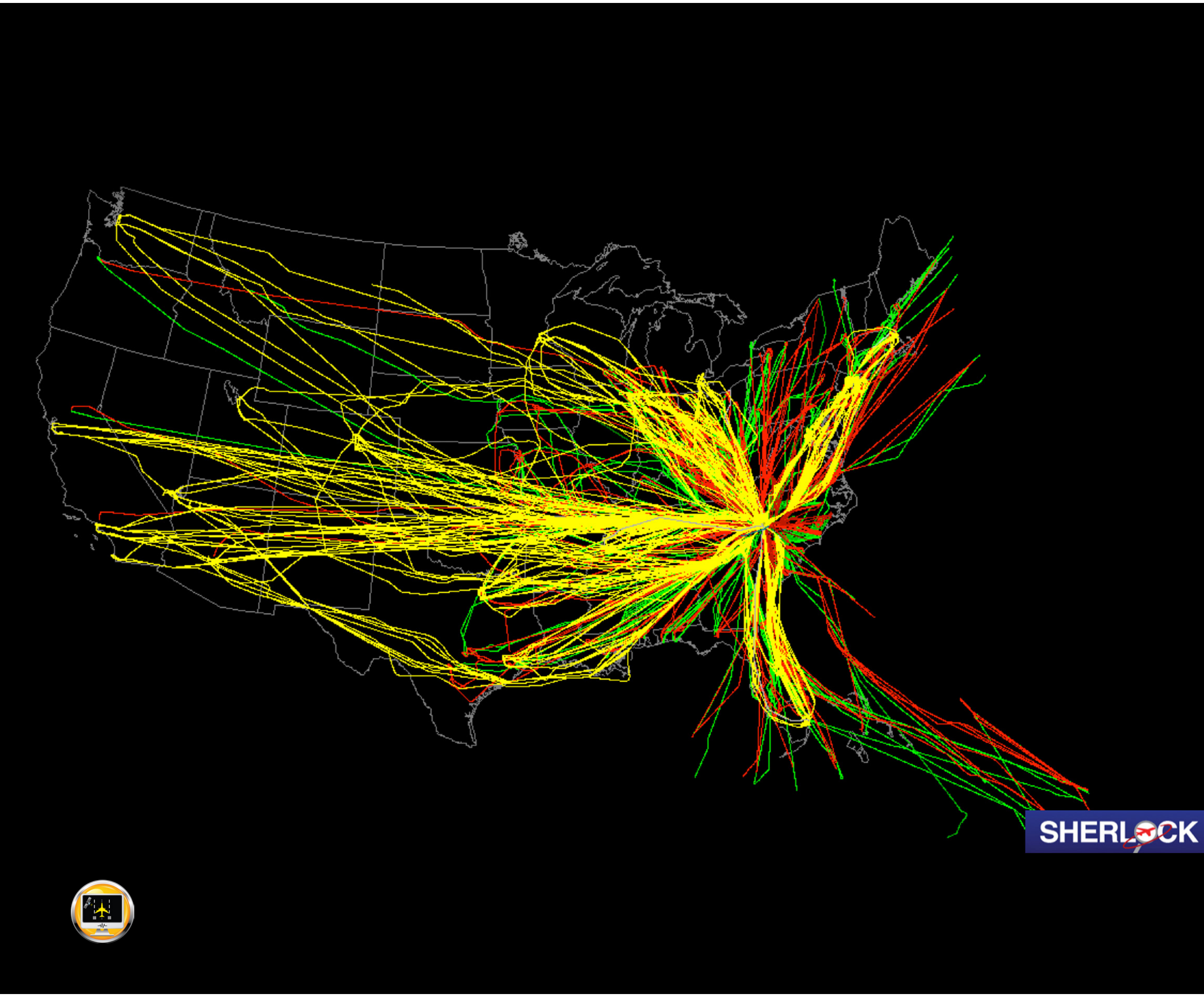
The Research Themes described in Table 7, below, support the Outcomes associated with Strategic Thrust 4.

Table 7. Outcomes and Research Themes for Strategic Thrust 4

STRATEGIC THRUST 4: TRANSITION TO ALTERNATIVE PROPULSION AND ENERGY			
	2015	2025	2035
Outcomes	Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems	Initial Introduction of Alternative Propulsion Systems	Introduction of Alternative Propulsion Systems to Aircraft of All Sizes
Research Themes	**Alternative Power, Propulsion, and Vehicle Architectures** Research and development of clean, quiet, and efficient transformative alternative integrated energy, power, and propulsive systems with synergistic vehicle-level integration **Alternative Fuel Combustors and Environmental Impact** Research and development of engine/fuel system integration, optimization, and performance including characterization of emissions and environmental impact **Electrified Aircraft Propulsion Components and Technology** Research and development of electrical components (e.g., electric machines, converters) and enabling technologies (e.g., materials, controls) that address weight, efficiency, and altitude challenges unique to flight **Modeling, Simulation, and Test Capability** Research and development of innovative tools and methods (computational, experimental, analytical) to transform power and propulsion system capability in less time with reduced uncertainty and cost		

Major Outcome Risks Addressed by Planned Research

- Significant research outside ARMD in critical areas such as batteries and electric motors affords sources for leverage, but targeted research is needed to address significant differences in requirements for aircraft applications.
- Without validated design and analysis tools and ground and flight tests, adoption of new propulsion concepts is very high risk, which would slow the transition of aviation to a low-carbon future.
- Without validated design and analysis tools, and ground and flight tests, integration of electrified aircraft propulsion architectures into to practical small air vehicles will slow and delay the opening of new aviation markets



NASA's Sherlock Air Traffic Management Data Warehouse shows one day of air traffic for Charlotte-Douglas International Airport. Image credit: NASA Ames

Strategic Thrust 5:

Real Time System-Wide Safety Assurance

This section describes Strategic Thrust 5, as well as a community vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust. It includes the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust. Further planning for this Strategic Thrust will benefit from a study of research requirements for real time system-wide safety assurance by the Aeronautics and Space Engineering Board of the National Academies of Sciences, Engineering, and Medicine scheduled for completion in 2017.

Community's Vision

Decades of continuous efforts to reduce risk in commercial aviation have made it the safest mode of transportation. 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 safety issues as they emerge and 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 ensure safe operations in more complex airspace by accelerating the proactive detection, prognosis, and resolution of emergent threats to system-wide safety. The result will be a safety net that utilizes system-wide data to provide alerting and mitigation strategies in real-time to address emerging risks.

Outcome for 2015-2025: Domain Specific In-Time Safety Monitoring and Alerting Tools. Over the next decade (2015-2025), developments in data mining and analysis, prognostics, real-time system assurance techniques, and safety risk modeling will support increased access to safety relevant data, expanded system awareness, and initial integration of analysis capabilities. Safety will be improved through initial real-time detection and alerting of hazards at the domain level and decision support for limited operations.

Outcome for 2025-2035: Integrated Predictive Technologies with Domain Level Application. The subsequent decade (2025-2035), will see NAS-wide availability of more fully integrated real-time detection and alerting capabilities for enhanced risk assessment and initial assured human and machine decision support, enabling selection of mitigating responses in increasingly complex operations.

Outcome for >2035: Adaptive Real-time Safety Threat Management. Beyond 2035, NAS-wide safety assurance will feature fully integrated threat detection and assessment capabilities that support trusted methods for dynamic, multi-agent planning, evaluation, and execution of in-time risk-mitigating response to hazardous events.

ARMD's Role

Strategic Thrust 5 focuses on research that incorporates secure sensor and networking technologies, along with innovative 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 (2015-2025), ARMD research will focus on initial continuous real-time monitoring, real-time anomaly and precursor identification and alerting of known safety hazards, mitigation response capability for selected applications, and assured access and analysis of secure data.

Research for the mid-term (2015-2025) will enable integrated system-wide continuous monitoring of safety margins and, trustworthy decision support tools that manage uncertainty to enable in-time hazard mitigation.

Beyond 2035, ARMD research will focus on real-time intelligent safety monitoring through integrated threat detection, prediction, and decision support to enable dynamic human-automation hazard mitigation strategies.

Research Themes

The Research Themes described in Table 8, below, support the Outcomes associated with Strategic Thrust 5.

Table 8. Outcomes and Research Themes for Strategic Thrust 5

	STRATEGIC THRUST 5: REAL-TIME SYSTEM-WIDE SAFETY ASSURANCE (RSSA)		
	2015	2025	2035
Outcomes	Domain Specific In-time Safety Monitoring and Alerting Tools	Integrated Predictive Domain Level Application	Adaptive Real-time Safety Management
Research Themes	**Continuous System-wide Safety Awareness (Monitor)** Technical approaches and required architecture to support comprehensive 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 RSSA technologies within all elements of the airspace		

Major Outcome Risks Addressed by Planned Research

- Access to sensitive data from all elements of the system is essential for both the development of validated tools and effective real-time monitoring.
- Processes and tools for data protection, as well nontechnical aspects of building trust within the community, will be critical.

Drone Co-habitation Services operates a Phantom 3 commercial multi-rotor unmanned aircraft, one of 11 vehicles in the UTM TCL2 demonstration that will fly beyond line of sight of the pilot in command in Nevada test. Image credit: NASA Ames/ Dominic Hart

Strategic Thrust 6:

Assured Autonomy for Aviation Transformation

This section describes Strategic Thrust 6, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust. It includes the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

This Thrust incorporates recommendations of the National Academies report, Autonomy Research for Civil Aviation.[14] 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.

Community's Vision

The evolution of autonomous systems will transform aviation operations, 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 advanced UAS operations and on-demand personal air transportation. The objective of Strategic Thrust 6 is to enable autonomous systems that employ highly intelligent machines to maximize the benefits of aviation to society.

Outcome for 2015-2025: Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals. This period will see the introduction of initial adaptive automation functions within airborne and ground-based systems, assured by limiting envelopes of applicability. Functions will include machine-based strategic control of systems, advisory support of humans in planning and decision making, and prognostics-based safety. Some functions will improve design and manufacturing processes and increase machine-to-operator ratio. New capabilities enabled by use of autonomous systems will be introduced, especially for UAS applications.

Outcome for 2025-2035: Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals. Advanced machine learning and adaptation capabilities will be introduced, assured through advanced prognostic approaches. Goals for autonomous functions will be specified at high level, and increased trust will facilitate widespread certification and implementation. For many systems, humans and machines will work as team peers to accomplish goals. Autonomous systems, made up of interconnected autonomous functions, will increase in scale. Systems

14 National Research Council of the National Academies. "Autonomy Research for Civil Aviation: Toward a New Era of Flight." National Academies Press, 2014

will learn and adapt through access to large quantities of data, enabling sophisticated world models of system states and the operating environment.

Outcome for >2035: Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals. Aviation applications possible only through advanced autonomy will predominate. 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. Goals will include system-level maintenance, healing, and protection. Systems will be interconnected and rely on high-resolution world models generated using massive distributed sensor networks. 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. The research will employ sophisticated testbeds to understand key challenges and develop solutions for specific applications.

ARMD's primary role will be in development of concepts, architectures, and applications for autonomous aviation systems, addressing critical autonomy barriers that require unique NASA contributions. ARMD will leverage initial technologies to insert autonomy into operational environments, and then build on experience, as well as conduct research to develop and demonstrate radical breakthrough autonomy concepts, technologies, and mission products. Research will include development of mission products that leverage the explosive growth and rapid development cycles of unmanned aerial systems. ARMD will provide community coordination and leadership to achieve research advances, implement selected applications, and leverage large investments in non-aviation autonomy technologies by repurposing those technologies for aviation.

In the near-term (2015-2025), ARMD research will focus on advanced prescribed automation and initial goal-directed and adaptive automation, initial world models and world views from local sensors and limited data exchange, and predominantly human-supervised; higher levels of machine independence under carefully controlled conditions, with applications to aviation system components and small-scale systems, including UAS.

Research for the mid-term (2025-2035) will focus on mission-level goal-directed adaptive automation, large-scale detailed world views using advanced sensors and networks, human/machine teams with many levels of control, depending on specific situations, and extensive machine-based learning applied to large-scale integrated systems.

Research for the far-term (>2035) 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

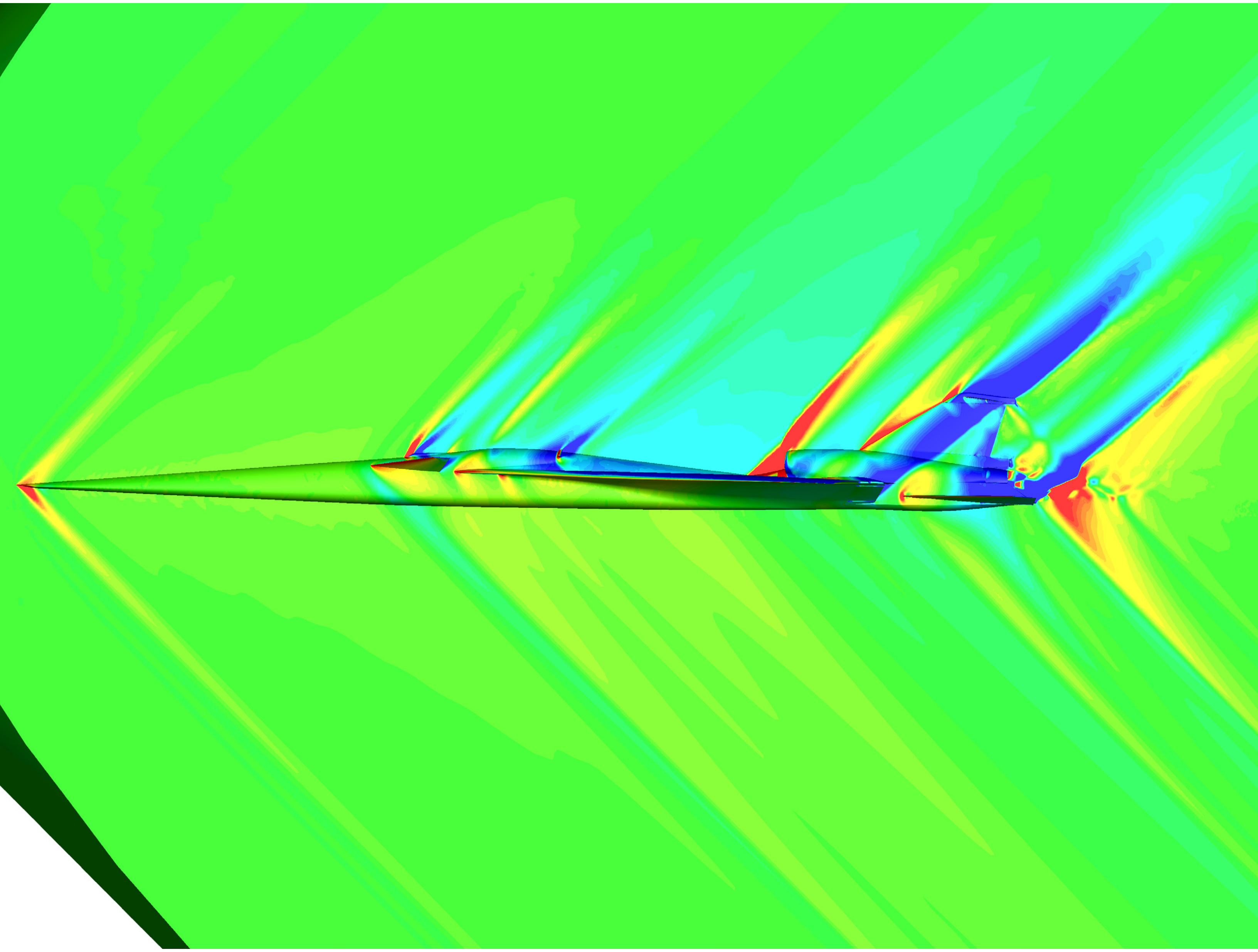
The Research Themes described in Table 9, below, support the Outcomes associated with Strategic Thrust 6.

Table 9. Outcomes and Research Themes for Strategic Thrust 6

	STRATEGIC THRUST 6: ASSURED AUTONOMY FOR AVIATION TRANSFORMATION		
	2015	2025	2035
Outcomes	Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals	Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals	Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals
Research Themes	**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 **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 Risks Addressed by Planned Research

- Strategic partnerships will be critical to maintaining awareness of unknown issues and risks, as well as providing opportunities to explore unique solutions.
- Verification and validation challenges must be addressed as a key factor affecting the pace of progress.
- Nontechnical issues, such as legal liability, public acceptance, moral decision making, and transformation of human roles and tasks, could pose barriers to applications of UAS and other uses of machine intelligence.



A supercomputer-generated visualization of the pressure field over a conceptual design of the Quiet Supersonic Technology demonstrator, or QueSST. Image credit: NASA/James Jensen

Crosscutting Research & Testing

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

Crosscutting research falls mainly into two areas: (1) next-generation physics-based modeling and design capabilities to enable realization of long-term vehicle and aviation system design concepts, and (2) enabling transformation of flight capabilities through innovations in discipline-oriented technologies such as new materials, measurement techniques, and flight and propulsion controls.

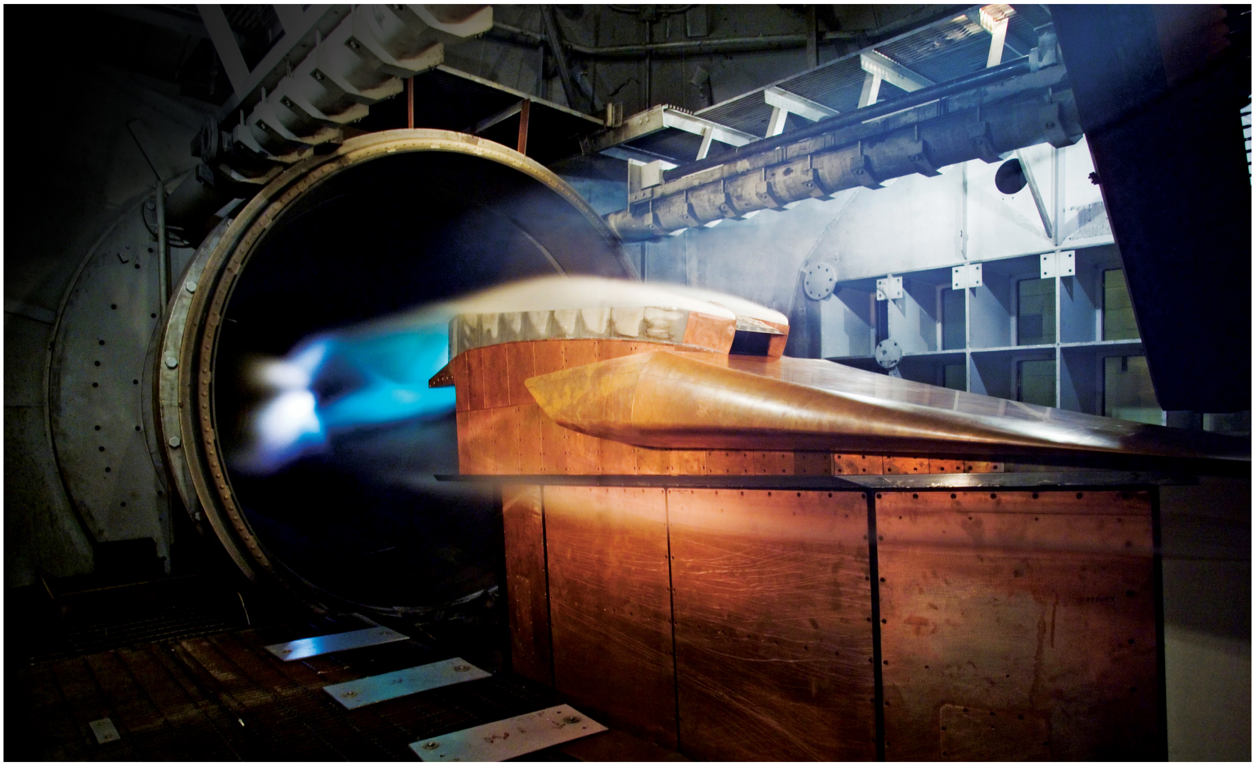
Research in revolutionary tools seeks to develop a multidisciplinary computational capability for modeling a broad range of phenomena of interest to aeronautics, including turbulent flow, transition, supersonic flow, reacting flow, acoustics, and other aspects of fluid physics, as well as development and validation of autonomous vehicle system control concepts enabling rapid progress from concept to flight. This research includes a range of capabilities, from system-level air vehicle design, analysis, and optimization tools, to high-fidelity computational fluid dynamics and structural and aeroelastic dynamics tools. Innovative numerical algorithms will take advantage of new computer architectures to make computational analysis faster and more efficient. Targeted validation experiments will develop databases for model assessment and validation, as well as providing insight for development of improved modeling ideas.

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. These technologies range from new materials that enable improved capability, to novel sensors, to advanced actuators. 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 and applied research on reducing the barriers to reusable hypersonic systems provides one example of incorporating advancements across multiple disciplines to support an application. ARMD will further integrate hypersonics in future versions of this plan.

ARMD will conduct fundamental and applied research to enable a broad spectrum of hypersonic systems and missions by advancing the core capabilities and critical technologies for hypersonic flight. The resulting technology advancements will be a benefit to national hypersonic programs. Efforts will be informed by and aligned to a national strategy with a balance between fundamental research and supporting and leveraging the work of the Department of Defense through continued close collaboration. Analytical tools, test techniques, and fundamental capabilities will reduce the barriers to routine, reusable hypersonic flight. ARMD will 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 hypersonic propulsion systems. ARMD will also 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 hypersonic vehicles a reality. Key to the mission will be engaging, invigorating, and training the next generation of engineers.

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, to 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 aircraft 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.



The X-51A team of the Air Force, Defense Advanced Research Projects Agency (DARPA), NASA, Boeing, and Pratt & Whitney successfully test a scramjet engine at hypersonic speeds inside the 8-Foot High Temperature Tunnel at NASA's Langley Research Center. Scramjet engines operate at very high speeds, but theoretically maintain the efficiencies of conventional turbine engines. A scramjet could someday power an aircraft to a location in minutes instead of hours. Image credit: NASA/Paul Bagby

Every U.S. aircraft and U.S. air traffic control tower has NASA-developed technology on board, working to improve performance and efficiency.

Conclusion

The coming decades represent both a great opportunity for aviation to serve a growing demand driven by global socioeconomic development and a major challenge to do so with minimum adverse impact on the environment. NASA's aeronautical research, carried out by ARMD, will play a leading part in enabling an efficient, flexible, scalable, and environmentally sustainable aviation system that will meet global needs for air transportation through 2035 and beyond. These needs are shaped by three Mega-Drivers: global growth in demand for high-speed mobility, global climate change, sustainability and energy use; and technology convergence.

More and more, aviation continues to do business in a global marketplace, and it continues to be a technology-driven industry. Although the U.S. long led the global aviation community, Airbus now develops and markets commercial airliners at parity with Boeing, while Brazil and Canada are delivering new narrow-body airliners and China is developing an indigenously designed commercial twin-jet. Overall, Boeing projects that 83% of the sales volume for commercial aircraft from 2016 to 2036 will be outside North America, with Asia at 40% and Europe at 19%[15]. Moreover, international companies are leveraging new technologies to pioneer innovative aviation products; for example, DJI, a Chinese company, is reported to have a greater than 50% share of the U.S. market for small UAS, or drones.

Thus, in addition to serving the needs of domestic users of aviation and airspace, NASA will continue to play a vital role in maintaining competitiveness of the U.S. civil aviation industry by conducting research outside the economic and risk criteria that govern commercial investments. In this global environment, ARMD will continue to develop and apply new technologies and promote innovation to support six Strategic Thrusts:

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Commercial Vehicles
- Transition to Alternative Propulsion and Energy
- Real-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. Viewing the NAS as a complex system of systems and working closely with the aviation community, ARMD research will leverage new or nontraditional technologies and approaches, including alternative fuels and electric or hybrid propulsion, low-sonic-boom supersonic flight, automation and autonomy, and technology convergence to develop transformative solutions. The ultimate goal is to enable a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system to meet the challenges of the future.

Join the Conversation

This Strategic Implementation Plan 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*

15 The Boeing Company, "Current Market Outlook 2016-2035." 2016

Acronyms List

3-D	Three-dimensional
AAVP	Advanced Air Vehicles Program
AOSP	Airspace Operations and Safety Program
ARMD	Aeronautics Research Mission Directorate
ATAG	Air Transport Action Group
ATM	Air Traffic Management
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
CAST	Commercial Aviation Safety Team
CFD	Computational Fluid Dynamics
CLEEN	Continuous Lower Energy, Emissions, and Noise (Program)
CNG2020	Carbon Neutral Growth 2020
CO_2	Carbon Dioxide
dB	Decibel
DoD	Department of Defense
EM	Emerging Market
EPNL	Effective Perceived Noise Level
EU	European Union
FAA	Federal Aviation Administration
IASP	Integrated Aviation Systems Program
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
NACA	National Advisory Committee for Aeronautics
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis
NextGen	Next Generation Air Transportation System
NO_x	Nitrogen Oxides
PLdB	Perceived Loudness Decibel
R&D	Research and Development
SESAR	Single European Sky Air Traffic Management Research
TACP	Transformative Aeronautics Concepts Program
TBO	Trajectory Based Operations
TRL	Technology Readiness Level
U.S.	United States
UAS	Unmanned Aircraft System(s)
VTOL	Vertical Takeoff and Landing

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