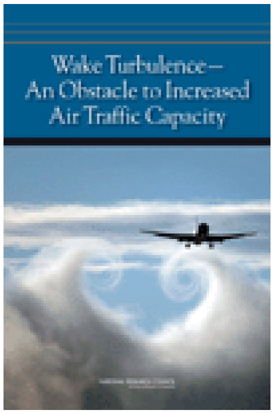

Wake Turbulence: An Obstacle to Increased Air Traffic Capacity

Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development Program, National Research Council

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THE NATIONAL ACADEMIES
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Wake Turbulence—An Obstacle to Increased Air Traffic Capacity

Committee to Conduct an Independent Assessment of the Nation's
Wake Turbulence Research and Development Program

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Preface

Demand for air transportation continues to increase rapidly and is projected to double or even triple by 2025. The present air transportation system cannot accommodate such a large increase in demand and in many places is already stretched, resulting in frequent and lengthy delays.

In the early part of this decade, government agencies and Congress recognized that continued incremental improvements would not provide the capacity needed in the coming decades; a different approach was required. Congress responded by enacting Public Law 108-176, Vision 100—Century of Aviation Reauthorization Act. It included a framework to accomplish a major transformation of the nation's air transportation system through the cooperation of the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the Department of Homeland Security (DHS), the Department of Transportation (DOT), the Department of Commerce (principally the National Oceanic and Atmospheric Administration, NOAA), the Office of Science and Technology Policy (OSTP), and the Department of Defense (DOD). The resulting Joint Planning and Development Office (JPDO), which includes representation from all of those organizations, is working on a wide-ranging set of programs that aim to make major changes to the air transportation system. Called the Next Generation Air Transportation System, or "NextGen," the system will have greater capacity to accommodate the increased air traffic demand projected for around 2025.

The Global Positioning System (GPS) constellation of some two dozen satellites provides remarkably accurate positioning and timing capability, far better than that provided by existing radar surveillance and ground-based navigation systems. Since determination of aircraft spacing en route and for approach and landing is affected by inaccuracies inherent in existing systems, one goal of NextGen involves taking advantage of GPS to enable aircraft to fly more closely spaced without diminishing safety. Developments in avionics, surveillance, navigation, and landing techniques based in whole or in part on GPS have, in the last 10 years or so, demonstrated that this is indeed possible. The use of GPS can practically and safely permit much closer flying.

Unfortunately, the accuracy of GPS does not solve the problem of wake turbulence. As an inevitable product of lift, an aircraft wing generates a wake in its trail. The heavier an aircraft is, the stronger its wake; the greater an aircraft's wingspan, the longer a wake will persist. This wake can be a safety hazard when smaller aircraft follow relatively larger aircraft too closely—a few accidents have demonstrated this fact clearly. In the early 1970s, the B747 was introduced—a much larger aircraft by far than the B707 and other similar aircraft of the time. To address the wake turbulence problem, the FAA introduced separation standards based on aircraft size. These standards have since been modified somewhat, but the principle remains: Aircraft are designated small, large, or heavy[1] based on their maximum takeoff weights. A heavy aircraft must be followed no more closely than 4 miles by another heavy aircraft, no more closely than 5 miles by a large aircraft, and no more closely than 6 miles by a small aircraft if the following aircraft is at the same altitude or less than 1,000 feet below. However, these standards are quite conservative. For example, the 4-mile spacing between a heavy aircraft and a large aircraft applies equally to large aircraft weighing between 50,000 and 250,000 lb, and the heavy aircraft can weigh anywhere from 255,000 lb to over 900,000 lb (the heaviest B747 in service). The new A380, weighing in at 1.2 million pounds, has been given larger spacing requirements by the International Civil Aviation Organization.

Recognizing the potential obstacle to capacity growth presented by the wake vortex hazard and that little had changed in establishing these standards in over three decades, in the 2005 National Aeronautics and Space Administration Authorization Act (P.L. 109-155) Congress directed NASA to contract with the National Research Council (NRC) to conduct a study of the issue. NASA and the NRC developed a statement of task

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[1] The International Civil Aviation Organization (ICAO) standards, used in Europe, use slightly different categories: light, medium, and heavy.

that included three steps. First, in the context of addressing the air traffic capacity issue, the study was to identify wake vortex research challenges, suggest a plan for accomplishing them, and recommend responsible agencies. Second, the study was to identify ongoing U.S. government research, including gaps and how to address them to best contribute to improved air traffic capacity. Finally, that review was to be expanded to include non-U.S. government research as well as research and information exchange partnerships, recommending any changes deemed necessary.

The Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development Program found that the wake vortex problem does present a real impediment to increased air traffic capacity, something reflected in most of the documentation that has been drafted to date by the JPDO. Most aircraft can clear a runway in less than 1 minute from touchdown to turnoff. However, wake vortex separation standards require a separation of 2 minutes or more, leaving the runway used only half as much as it might be. The need to address wake vortex limitations is clearly articulated throughout the NextGen planning documents, the concept of operations document, and the research presentations reviewed by the committee. However, although the need to address wake vortex issues is clearly acknowledged, the research required to provide the required solutions is not yet under way.

While European agencies are conducting research on a wide variety of wake vortex issues, there is little such work ongoing in the United States. In part, this is the result of reductions in aeronautics research funding. Recent aeronautics research funding reductions applied to the NASA budget have resulted in a realignment and reprioritization of NASA's research work. Prior to the cuts, NASA and the FAA pursued a partnership of research programs. The FAA focused on near-term operational issues. NASA provided the technical support that the FAA lacked and also sponsored and conducted more fundamental, long-term research. At present, NASA's budget can no longer support the FAA's short-term activities, nor is much funding available for long-term fundamental research. The committee saw gaps in the technical research effort in terms of technical support to the FAA's ongoing, relatively near-term research that promises capacity improvement, in long-range, higher-risk but potentially high-payoff research work, and in the modeling needed to advance fundamental understanding of wake behavior. The committee also noted that in many cases, small-scale weather can actually dominate vortex spacing considerations. Favorable winds may transport the wake out of the flight path of following aircraft. Unfavorable winds may transport a wake into the flight path of an aircraft on a parallel course. Understanding what measurements are needed to take advantage of these short-term weather fluctuations is key to permitting safe adjustments to wake vortex separation standards. To claim this potential capacity, research is needed to move this effort ahead now.

The committee was fortunate to have as members knowledgeable volunteers, some retired, with experience in a broad range of disciplines, and representing a cross section of the academic, industrial, and government communities. The diversity of the group made for enthusiastic discussion and debate, which in turn facilitated getting the task done efficiently in only three meetings in Washington, D.C. The members' unselfish efforts made the task do able, and the committee's work was made much easier by the superb support provided by the National Academies' staff, particularly Kerrie Smith, program officer, and Sarah Capote, program associate. Without their able assistance throughout the study, the committee would have been far less efficient and informed.

Anthony J. Broderick, *Chair*
Committee to Conduct an Independent Assessment
of the Nation's Wake Turbulence Research and
Development Program

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Thomas Gerz, DLR,
Preston Henne, Gulfstream,
Ilan Kroo, Stanford University,
Jack Olcott, General Aero Company, Inc.,
Turgut Sarpkaya, Naval Postgraduate School, and
Roger Wall, FedEx.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis Lanzerotti, New Jersey Institute of Technology. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Wingtip vortices were first described by British aerodynamicist F.W. Lanchester in 1907. A product of lift on a finite-span wing, these counter-rotating masses of air trail behind an aircraft, gradually diffusing while convecting downward and moving about under mutual induction and the influence of wind and stratification. Should a smaller aircraft happen to be following the first aircraft, it could be buffeted and even flipped if it flew into the vortex, with dangerous consequences. Given the amount of air traffic in 1907, the wake vortex hazard was not initially much of a concern.

Times have changed. The demand for air transportation continues to increase, and it is estimated that demand could double or even triple by 2025. One factor in the capacity of the air transportation system is wake turbulence and the consequent separation distances that must be maintained between aircraft to ensure safety.

In 2005, Congress passed the 2005 National Aeronautics and Space Administration (NASA) Authorization Act (P.L. 109-155), which, inter alia, directed the NASA administrator to enter into an arrangement with the National Research Council (NRC) to assess federal wake turbulence research and development (R&D) programs to address whether the federal R&D goals and objectives were well defined, whether there were any deficiencies in them, and what roles should be played by each of the relevant federal agencies: NASA, the Federal Aviation Administration (FAA), and the National Oceanic and Atmospheric Administration (NOAA, part of the Department of Commerce). This report is the result of that assessment, based on the statement of task (see Appendix A) developed by NASA's Aeronautics Research Mission Directorate and the NRC in accordance with the congressional direction. Chapter 5 lists all findings and recommendations; this summary highlights some of them.

WAKE TURBULENCE IS AN OBSTACLE TO INCREASED CAPACITY

The frequency of air traffic delays reached an all-time peak in June 2007, and that frequency is only expected to grow. The current air transportation system has reached a limit in certain airspaces, particularly near hub airports, where increasing traffic density and current routing practices necessitate a new approach to air traffic spacing and control. The interagency Joint Planning and Development Office (JPDO) was established to usher in the Next Generation Air Transportation System (NextGen). The seven entities represented in the JPDO are the FAA, the Department of Transportation (DOT), NASA, the Department of Homeland Security (DHS), the Department of Commerce (principally NOAA), the Office of Science and Technology Policy (OSTP), and the Department of Defense (DOD).

NextGen is expected to bring revolutionary changes in navigation, communications, and air traffic control, all designed to increase the capacity of the air transportation system. At most airports, this will mean more aircraft arriving and departing. Depending on their relative sizes, a certain minimum separation distance between aircraft must be maintained during approach and landing to avoid wake vortex encounters. Unless the separation distance can be reduced, other NextGen technologies will have much less impact on arrival and departure capacity than they otherwise could be expected to have.

When the Boeing 747 entered the airspace system in 1970, it was substantially bigger than the existing commercial aircraft. As a result, wake vortex separation criteria were developed based on then-available technology. Though there have been a few revisions to the criteria over the intervening years, the state of the art has not provided a basis for substantial changes. In many cases, these wake vortex separation requirements do not allow taking advantage of reduced separation standards enabled by satellite and other new technologies.

In the past, the focus of wake turbulence research was aimed at improving safety. Current wake vortex separation criteria are conservative and sufficient for ensuring safe operations. The key question now is whether a reduction in wake vortex separation criteria can be obtained while maintaining safety. Unfortunately, there is still no way to judge how much this spacing can be reduced—that is, there is no clearly defined "hazard boundary." With no meaningful metric, it is impossible to tell whether a proposed alternative is acceptably safe.

The Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development Program concluded that there are both organizational and technical challenges involved in increasing air transportation system capacity through reducing aircraft separation standards. It also recognized that reducing separation standards is only one factor in increasing air system capacity. Some airports may not be able to take advantage of the extra capacity afforded by reduced separation standards. Today's aviation system is a complex web of intertwined systems that constrain each other in nonobvious ways. Runways, taxiways, gates, terminal traffic, emissions, and many other factors may limit capacity to much the same extent as wake turbulence does. Studies of tradeoffs at individual airports and at the systems level are useful in identifying the most fruitful ground for improvement. Thus, while wake turbulence is *an* obstacle to increased capacity, it is not the only obstacle. The others are outside the scope of this committee's charge, however.

Finding 1-1. Air transportation system capacity could be significantly enhanced by applying the results of robust and focused wake vortex research and development. These results will be required in order to use the system at its maximum efficiency.

Recommendation 1-1. Aircraft wake vortex characteristics of transport airplanes operating in the national airspace system should be assessed using the best standardized techniques prior to their introduction into service, so that appropriate separation criteria may be established with regard to each new aircraft model. The details of this assessment should vary based on the impact any new aircraft is expected to have on the system, with large and heavy aircraft receiving more emphasis than small ones in terms of data requirements.

ORGANIZATIONAL CHALLENGES: FEDERAL WAKE TURBULENCE RESEARCH NEEDS LEADERSHIP

To best support a national approach to overcoming wake turbulence challenges, there needs to be a simple and clearly defined goal, agreed to and understood by all participants. Based on current needs, an appropriate goal would be to develop the technical and procedural capability to increase capacity—without loss of safety—by reducing the required aircraft separation distances associated with wake turbulence avoidance.

Historically, NASA and the FAA shared leadership of wake turbulence research. This arrangement was successful when budgets were not so tight, but it is no longer feasible. While NASA has the technical expertise to support this leadership, wake turbulence research now lies outside its priority research funding focus. The FAA is responsible for the establishment of civil aviation safety standards and implementation of air transportation system changes, and therefore has an interest in all phenomena that affect safety, including wake turbulence. The JPDO has the ability to coordinate research, but as a planning agency it does not have the necessary executive power or budget authority. NOAA and DOD occasionally contribute to wake turbulence research, but their efforts are motivated by their own needs, not by the goal of increasing the capacity of the air transportation system. Without a leader, the alignment of these efforts depends on the relationships between individual researchers and on temporary partnerships between agencies. This is sufficient leadership to ensure success in projects and programs that take place over a few years, but not enough to tie those successes together into solutions.

Finding 2-1. There is no champion, spokesperson, or leader held accountable for goal achievement across the nation's wake turbulence research and development efforts.

Finding 2-2. Wake turbulence is a long-term problem. Although a total solution cannot be achieved within a decade, improvements will become available gradually, depending on funding, and it can be envisioned that these incremental improvements will provide incrementally increased capacity at airports where implemented.

Recommendation 2-1. Federal wake turbulence research should have the following characteristics:

- **The FAA should be the lead agency for defining requirements for wake turbulence research.**
- **The FAA should manage and fund capacity-focused wake turbulence research using academic, industry, and other government partners.**
- **The FAA should appoint a strong and motivated leader to integrate and coordinate research across agencies, define priorities, and represent wake vortex research to the JPDO and other agencies.**
- **Research should be sustained over the short, medium, and long term.**
- **Resource allocations across functional lines of involved agencies should be coordinated among all agencies involved in this work.**

Better coordination of the many independent entities that are currently studying wake turbulence characteristics, dynamic predictive capabilities, sensor and display development, and adaptive procedures will be important. Until recently, NASA provided essential fundamental wake turbulence research in partnership with the FAA. But budget constraints have severely limited NASA's ability to support the wake vortex research required for NextGen, creating a technology gap. While NASA is still well-aligned to do this research, in that it possesses the proper expertise, facilities, and institutional experience, it does not have the necessary resources. The FAA does not have this expertise, and there appears to be no other government agency with this capability or capacity. Other organizations with this technical capability will have to be identified so that the FAA can work with them.

Elements of a successful study of wake turbulence include (1) being identified as a major program within NextGen, the wide ranging transformation of the entire national air transportation system; (2) being included within the scope of one or more of the FAA Air Transportation Centers of Excellence; (3) being consolidated in a single location, perhaps at the FAA Field Office located at NASA's Langley Research Center, funded by the FAA; (4) being identified by the Administration as a high priority; (5) being closely linked to all similar international studies; and (6) being identified as a high priority in the Aeronautics Research and Development Plan and the related Aeronautics Research, Development, Test, and Evaluation Infrastructure Plan, as it was in the NRC's 2006 *Decadal Survey of Civil Aeronautics*.

The committee found as follows **(Findings 2-3, 2-4, and 2-5):** The change in aeronautics research priorities at NASA has led to a gap in the wake turbulence program as previously envisioned; present federal investment does not place sufficient priority on wake turbulence research to achieve the results called for by NextGen goals; and NASA expertise is well-aligned to conducting medium- to long-term fundamental research, including wake vortex modeling and wake vortex alleviation work, while the FAA does not currently have such expertise.

Recommendation 2-2. Because of its expertise, NASA should continue to conduct medium- to long-term fundamental research, including wake vortex modeling and wake vortex alleviation work at a level of effort sufficient to achieve NextGen goals.

Operators (including airline pilots, airline management, and general aviation pilots) and controllers are important elements of this process. If these parties are not confident that new operations and technologies are safe and effective, they will not use them. By engaging users, researchers will have a better understanding of what is and is not acceptable, and users will have a better understanding of new systems and be able to contribute to their development and implementation.

Recommendation 2-3. Operators and controllers should be included in the process of designing, implementing, and evaluating wake turbulence-related changes to the air transportation system.

The JPDO has an important role in assisting in the definition of federal wake turbulence research. Its Integrated Work Plan and its Research and Development Plan currently in development are expected to provide some guidance, but more detailed plans will be necessary to ensure that wake turbulence solutions will both support and be supported by the NextGen architecture.

Recommendation 2-4. JPDO should recommend to the FAA detailed wake vortex research efforts needed to support NextGen.

TECHNICAL CHALLENGES

The committee identified nine technical challenges that need to be addressed. Each is discussed in detail in Chapter 3, and associated milestones are identified for short-term (by 2012), medium-term (by 2017), and long-term (by 2025) research. The committee divided the technical challenges into three groups: capacity enhancers, enabling research, and supporting studies.

Capacity Enhancers

Improving Spacing System Design

The committee considered three approaches (see **Findings 3-2**, **3-3**, and **3-4** and **Recommendations 3-2**, **3-3**, and **3-4**):

- *Closely spaced parallel approach (CSPA) procedures.* Wind monitoring will allow better use of parallel runways, because spacing can be reduced when the leading aircraft is downwind of its follower. When wind monitoring is coupled with improved technology on the vortex location and revised air traffic control (ATC) procedures, even greater capacities can be achieved.
- *Recategorization.* The current system of categorizing an aircraft as small, large, or heavy may not be the most efficient approach, particularly since it does not account for detailed characteristics of the wakes, or the encountering aircraft.

- *Dynamic spacing.* A combination of modeling and measurement that locates the wake vortices would allow aircraft to continually adjust their spacing in Visual Flight Rule (VFR) flight for optimization depending on the mix of aircraft approaching, the speed and direction of wind, and the rate of dissipation of vortices on approach to a given runway. In Instrument Flight Rule (IFR) flight, the system would provide a safety backup to assist in ensuring avoidance of a hazardous wake encounter.

Vortex Visualization: Cockpit and Controller

Dynamic spacing of aircraft based on wake vortex motion will require prediction of wind behavior over roughly the next hour. It is also necessary for the pilot and/or controller to have information on the wake position in real time as a safety net to verify the predicted separation provided. The information could be presented to the pilot numerically, visually, or by a simple red/green light system. One option for presenting the real-time wake position that has been researched is visualization. Onboard wake vortex visualization has been demonstrated in a proof-of-concept trial and can provide a safety net for dynamic self-spacing procedures in both IFR and VFR flight. These concepts should be further explored and pursued (see **Finding 3-5** and **Recommendation 3-5**).

Vortex Alleviation

There have been many attempts over the past several decades to evaluate systems that provide some alleviation of the wake vortices via laboratory simulations. The level of vortex alleviation activity in the United States is very small, with no discernible effort at any of the federal agencies. Activity over the past decade has been concentrated in industry, in academia, and in Europe. Vortex alleviation has the potential to significantly impact aircraft spacing requirements in the long term. Vortex alleviation ideas, including configuration changes and active and passive forcing, should be explored. (See **Findings 3-6 and 3-7** and **Recommendation 3-6.**)

Enabling Research

Weather Forecasting

European forecast models have already been demonstrated to forecast terminal area weather and wake vortex persistence in the short term. In the United States, existing weather forecast models have been used with some success at Lambert-St. Louis International Airport (STL) to forecast wake transport persistence. A higher-resolution model will be required to improve on this performance and to better forecast wake vortex persistence. The Weather Research and Forecasting (WRF) model currently under development by the National Center for Atmospheric Research, NOAA, DOD, the FAA, the University of Oklahoma, and others has the potential to meet this requirement in the necessary time frame to support the needs of NextGen. However, as presently conceived these models lack the ability to incorporate eddy dissipation rates and thus will not provide the optimal set of parameters needed for predicting wake turbulence. More research is needed to ensure that weather modeling is adequate to predict wake vortex movement and decay. (See **Findings 3-8 and 3-9**, and **Recommendations 3-7 and 3-8.**)

Wake Vortex Modeling

Wake vortex modeling attempts to predict the basic characteristics of the vortices from the near field into the far field as a function of the generating aircraft and ambient atmospheric conditions. Modeling of the wake-initialization phase has not received much attention at any of the federal agencies. Recent efforts are focused in industry, in universities, and in European agencies. Modeling of the wake-evolution phase has been ongoing at NASA Langley Research Center, with research assistance from the Naval Postgraduate School and Northwest Research Associates. Wake vortex modeling plays a critical role in many concepts aimed at reducing IFR spacing requirements, and NASA's aeronautics program is well-aligned to conduct medium- to long-term foundational wake vortex modeling. (See **Findings 3-10 and 3-11.**)

Wake Vortex Measurement

Research and development of high-resolution sensors to support wake vortex modeling efforts has stalled since the late 1990s. Sensors are needed to measure aircraft wake vortices as well as meteorological conditions for inputs into wake vortex and weather prediction models. No high-resolution wake vortex measurement system capable of operating in inclement weather currently exists. An all-weather, aircraft-based wake vortex measurement system that provides information on the location of the wake should be explored, and an all-weather wake vortex measurement system that provides high-resolution measurements of wake vortex characteristics sufficient to validate wake vortex modeling should be developed. (See **Findings 3-12 and 3-13** and **Recommendations 3-9 and 3-10.**)

Supporting Studies

Safety Analysis and Hazard Boundaries

It is difficult to quantify acceptable reductions in wake turbulence spacing because there is no agreed metric for or definition of hazard boundaries for wake encounters. A "hazard boundary" provides a demarcation between acceptable and unacceptable vortex encounters based on criteria developed in conjunction with the pilot community. Because defining a hazard standard is ultimately the responsibility of regulatory bodies, this effort should be led by the FAA. However, substantial research at the aircraft vehicle level is required to define the wake hazard boundaries. This aspect of the work could be led by NASA, using contract support from aircraft manufacturers and airlines/pilots. A hazard boundary needs to be defined and used as a metric in forming spacing criteria. (See **Finding 3-15** and **Recommendation 3-11.**)

Systems to Gather Data About Wake Events

The challenge is to develop a means of collecting information and data from wake events that have actually occurred as observed and reported by pilots. Currently only a very limited amount of information on wake events is collected in any form by any agency in the United States, so baseline data are not readily available. Without an event-driven database as a control, it will be very difficult to measure whether any future increase or decrease in wake events is the result of reduced spacing or is simply in line with current event levels. Pilots and controllers today do not have a simple system to report the impact of a wake event in all phases of flight. Implementing a system to gather data on wake events in the short term could establish a baseline that could be used to quantitatively evaluate potential solutions. It could also help gain support from the operator and ATC community. (See **Finding 3-16.**)

System-Level Study of Benefits

System-level studies are required to assess the relative benefits of wake-turbulence mitigation strategies and to help with setting research priorities and using resources effectively. It is important that system-level studies cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts. They are essential for ensuring that (1) research priorities are set in a rational manner, (2) the actual realizable benefits of wake turbulence solutions will be known, and (3) key constraints can be identified and NextGen capacity goals can be achieved. The current JPDO research in system-level modeling of the air transportation system should be continued and resources should be directed to extending simulation capabilities to cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts. (See **Finding 3-17** and **Recommendation 3-12**.)

Agency Roles in Addressing the Challenges

Certain agencies are best able to address certain of these technical challenges. Over the short and medium terms, the FAA, assisted by NASA, should continue its current improved spacing programs, and it should pursue work to determine minimum runway spacing for future airport expansions (see **Recommendations 3-3 and 3-4**). The JPDO should do three things:

- Investigate and define specific requirements for research on the impact of cruise-altitude-generated wakes on capacity (including climb and descent) to avoid future problems as fleet diversity increases (**Recommendation 3-1**).
- Conduct a detailed analysis of what wake turbulence research and development is needed to achieve its separation management capability goals, and provide a detailed plan with milestones that will lead to successful development in the required time frame (**Recommendation 3-2**).
- Continue its research in system-level modeling of the air transportation system and direct resources to extending simulation capabilities to cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts in support of FAA and NASA research, as requested and agreed to in support of NextGen goals (**Recommendation 3-12**).

For the technical challenges that do not suggest a specific agency, the FAA should manage the program, utilizing resources such as WakeNet USA, a support network including academia, industry, and various federal research centers that coordinates federal wake turbulence research. These resources should be tapped whenever possible. Partnerships with this support system, as well as international partnerships—including continuation of work with WakeNet Europe—should be encouraged, striving for a balanced mix of participation.

CREATING A WAKE TURBULENCE PROGRAM PLAN

In addition to identifying technical challenges, the committee was charged with prioritizing those challenges and generating a draft program plan. The committee found that the challenges were highly synergistic, which made it very difficult to prioritize them as a single list; a particular challenge's ability to provide capacity was generally linked to the accomplishment of others, and thus contingent on the contents of the total research portfolio. The committee accordingly decided to roll prioritization and program planning into a single step.

Concurrently investigating capacity enhancers at varying stages of maturity reduces the technological risk of the program as a whole. Figure S-1 shows a notional program plan. Each challenge is accompanied by a bar stretching from the short term to the long term. The height of the bar represents the level of effort recommended by the committee; the shading of the bar represents its priority. The priorities and levels of effort were selected with the expectation that the program as a whole would have the greatest potential to create capacity; the expected deliverables of this program are listed in Table S-1. Because of the interrelationships among the challenges, budget changes should be absorbed by the program as a whole. That is to say, instead of cutting or eliminating one challenge in times of scarce resources, levels of effort should be lowered across the board, with medium-priority challenges taking a slightly larger cut than those with high priority. The committee did not judge any of the challenges to be of low priority. In this way, the time horizon of the program may grow longer, but the quality of the results will not be jeopardized. Similarly, if more money becomes available, it should be used to bolster efforts for all of the challenges.

That said, research is a dynamic enterprise. This report includes milestones (Table S-1) and metrics (Table S-2) for evaluating the progress in overcoming these challenges. In time, some may prove to be dead ends, or new ideas may surface, necessitating periodic reexamination of research priorities to ensure that wake turbulence research maintains relevance throughout the evolution of the NextGen system.

Recommendation 4-1. Wake turbulence research should pursue multiple tracks, with the goal of a robust, stable program that will provide continuing reductions in aircraft spacing as new ideas and technologies are developed and proven.

Recommendation 4-2. Wake vortex research priorities should be periodically reexamined.

Recommendation 4-3. The federal wake turbulence R&D enterprise should continue its relationships with a balanced mix of government laboratories, industry, and academia.

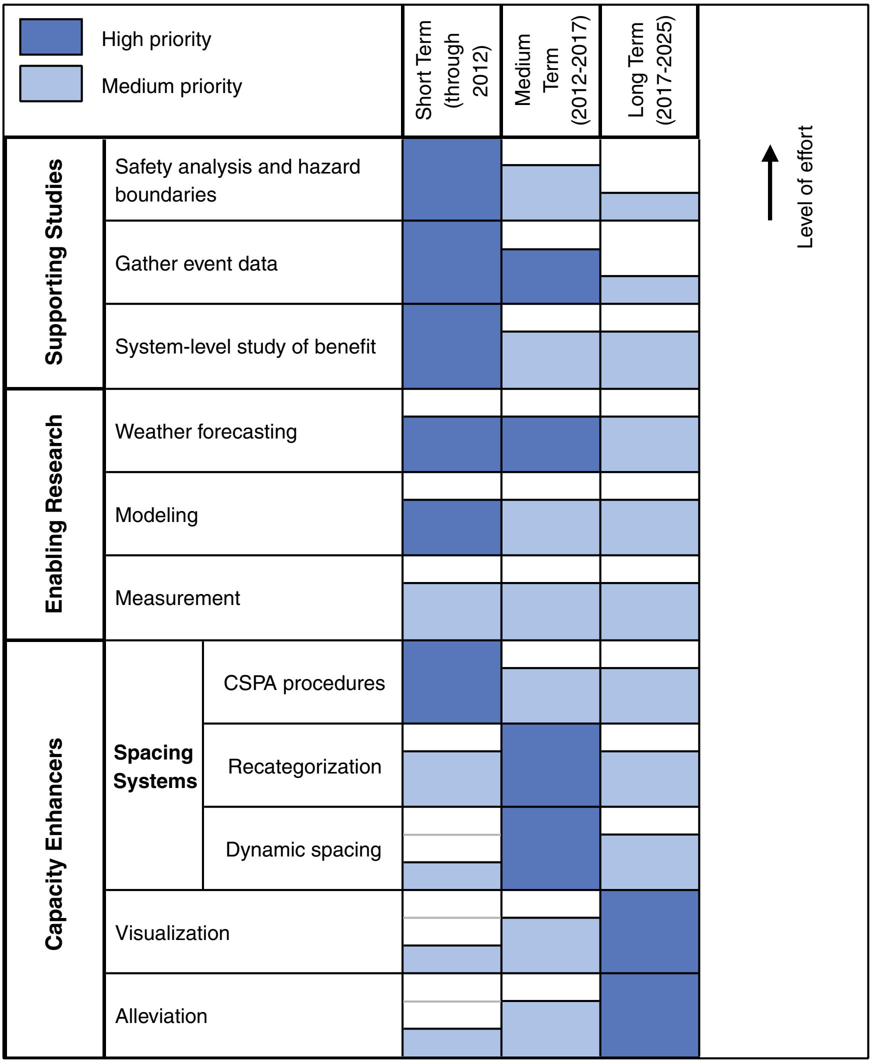

FIGURE S-1 Recommended priority and level of effort for wake turbulence challenges. Height of each bar indicates level of effort. Shade of each bar represents priority (darker corresponds to higher priority). CSPA, closely spaced parallel approach.

TABLE S-1 Deliverables

Short Term	Medium Term	Long Term
Conservative hazard boundary	Fleetwide simulation capabilities for gate-to-gate operations	Refined and tested hazard boundary
Outreach efforts to aviation community	All-weather wake vortex measurement system	Pilot training for wake vortex
Wake turbulence encounter reporting system	Airborne wake vortex sensor	System-level simulations with effects of uncertainty
System-level simulations of arrival/departure with operational scenarios, weather scenarios, fleet mixes, and airport layouts	Wake vortex measurement network	High-resolution, all-weather wake vortex measurement system
Weather data needs coordinated with WRF effort	Conditional spacing reduction to CSPA at selected airports	High-resolution, all-weather wake vortex measurement network
Probabilistic wake vortex model		Conditional spacing reduction to CSPA at all airports
		Conditional spacing reduction for single runway approaches at selected airports
		Visualization systems[a]
		Alleviation methods and devices[a]
		Dynamic spacing[a]

NOTE: WRF, Weather Research and Forecasting; CSPA, closely spaced parallel approach.

[a] Research would be completed in the long term, but deliverable would not yet be available.

TABLE S-2 Evaluation Metrics

	Metrics
Supporting studies	Number of parameters included in analysis Amount of data collected Variety of data collected Computational efficiency of models Applicability to flight simulators for pilot training
Enabling research	Temporal and spatial resolution Low uncertainty Weather tolerance Accuracy in the characterization of —Lateral wake location —Vertical wake location —Wake strength —Meteorological conditions Speed —Computational efficiency —Time response of measurement systems
Capacity enhancers	Capacity provided Delays reduced Cost Precision Accuracy Predictability (Will you know how much capacity you have?) Robust to —Airports —Aircraft —Weather conditions —Traffic conditions

1

Introduction

NEEDS OF NEXTGEN

Demand for air transportation continues to increase, and it is estimated that demand will double or even triple by 2025. The present air transportation system cannot accommodate such a large increase in demand.

Concerned that special efforts were needed to address this issue, Congress passed the Vision 100, Century of Aviation Reauthorization Act (P.L. 108-176) in 2003, establishing a framework for the Joint Planning and Development Office (JPDO) to facilitate activities in a wide-ranging initiative to transform the air transportation system. The Next Generation Air Transportation System (NextGen) aims to transform the U.S. air transportation system to accommodate a tripling of demand.

To do this, the implementation of new capabilities of technologies such as satellite-based navigation, surveillance, and networking needs to be accelerated, and new air traffic control (ATC) procedures need to be designed and employed. Significant advances in surveillance and navigation technologies have high potential to increase system capacity by substantially reducing aircraft separation distances during flight. It is the goal of NextGen to develop and oversee the implementation of these technologies in order to increase airspace system capacity and address increased demand.

There are a number of challenges that NextGen faces. These challenges may be operational, such as determining flight paths and reducing runway occupancy time. Taxes, fees, and ticket prices are economic challenges that feed into the way the system is funded. Other challenges are societal: airport expansion with its increases in noise and pollution, and the transportation infrastructure that allows people to get from their doorsteps to the airport. Finally, challenges in weather and wind conditions, including turbulence, gust, shear, and visibility, are physical in nature, and not the topic of this study. This report concerns just one of these many obstacles, a challenge that has both operational and physical aspects: wake turbulence.

All aircraft trail wake vortices as a consequence of lift developed in flight. The wake vortex can present a real danger to aircraft following each other, particularly when the leader is larger than the follower. When the Boeing 747 entered the airspace system in 1970, it was substantially bigger than existing commercial aircraft. As a result, wake vortex separation criteria were developed based on then-available technology. Though there have been a few revisions to the criteria over the intervening years, the state of the art has not provided a basis for substantial revisions. In many cases, these wake vortex separation requirements (discussed in the next section) prevent the use of reduced separation standards enabled by satellite and other technologies. This report reviews the nation's wake turbulence research and development program and assesses its ability to provide wake vortex avoidance and/or mitigation technologies that will permit achievement of the NextGen goals.

WAKE HAZARDS AND OVERVIEW OF CURRENT STANDARDS

There are no Federal Aviation Regulations specific to wake vortex hazards, either for certification or operations. Current aircraft separation standards related to wake vortex hazards have evolved over the past 40 years. Guidance material for pilots is contained in FAA Advisory Circular 90-23F: Aircraft Wake Turbulence (FAA, 2002), and in the FAA *Aeronautical Information Manual* (FAA, 2006a), updated semiannually. These publications contain educational and operational advisory information pertaining to aircraft operations in potential wake vortex situations, including pilot responsibilities. Pilot groups and industry associations have also issued advisory material to their constituents to raise awareness and provide guidance for avoiding and dealing with potential encounters. Pilots are generally well aware of this information and adhere to the recommended operating procedures for wake vortex avoidance. However, these procedures generally require pilots to observe the flight path of the wake-generating aircraft; therefore they are currently effective only in visual meteorological conditions (VMC), i.e., clear weather.

ATC aircraft separation standards and procedures for their use are contained in FAA Order 7110.65R: Air Traffic Control (FAA, 2006b). As larger and more diverse aircraft types have been introduced into the national airspace system, there have been re-categorizations of aircraft types and separation standard adjustments to ensure safety in all operating environments. Research has focused primarily on characteristics and behavior of wake vortex phenomena. Findings from this research have been used in the development, validation, or redefinition of the operational aircraft separation standards and procedures in use today.

Current separation standards are shown in Table 1-1. Agreement has been reached in the international aviation community regarding separation standards behind the Airbus A380. While the separation standards of FAA Order 7110.65R have generally proved to be safe and effective, they are much more conservative than visual separations, which can be achieved during VMC operations in accordance with Advisory Circular 90-23F and the *Aeronautical Information Manual*. Collective wisdom holds that air traffic capacity is greatly reduced in instrument meteorological conditions (IMC), compared to VMC, suggesting that spacing standards may be conservative. A 1978 study of observed VMC separation distances supports this interpretation (Haines, 1978; Table 1-2).

In the NextGen system, improved navigation and surveillance systems will have substantially increased accuracy and update rates. The pressure to increase capacity with these new systems will accentuate the importance of determining safe separation minima for wake vortex avoidance in all phases of flight: en route, terminal, and approaches to single runways or closely spaced parallel runways (CSPRs for the runways

TABLE 1-1 IFR Separation Requirements for Arrival on the Same Runway (NM)

	Trailing Aircraft		
	Heavy	Large	Small
Leading Aircraft	(max. takeoff weight of 255,000 lb or more)	(max. takeoff weight of 41,000-255,000 lb)	(max. takeoff weight of 41,000 lb or less)
Heavy	**4**	**5**	**6**
B757	**4**	**4**	**5**
Large	3(2.5)	3(2.5)	**4**
Small	3(2.5)	3(2.5)	3(2.5)

NOTE: Numbers in bold are based on wake vortex separations. Numbers in parentheses are valid only at certain airports. IFR, Instrument Flight Rule; NM, nautical mile. SOURCE: FAA, 2006b.

TABLE 1-2 Separation Distances Observed During Self-separation in VMC (NM)

	Trailing Aircraft		
	Heavy	Large	Small
Leading Aircraft	(max. takeoff weight of 300,000 lb or more)	(max. takeoff weight of 12,500-300,000 lb)	(max. takeoff weight of 12,500 lb or less)
Heavy	2.7	3.6	4.5
Large	1.9	1.9	2.7
Small	1.9	1.9	1.9

NOTE: There was a recategorization in 1996, so "small," "large," and "heavy" are not the same between Table 1-1 and 1-2. However, given that before the recategorization, "smallers" were smaller, and "heavies" were heavier, the point is made more strongly that IMC standards have been conservative. VMC, visual meteorological conditions; NM, nautical miles. SOURCE: Haines, 1978.

themselves or CSPAs for closely space parallel approaches). Automatic Dependent Surveillance-Broadcast (ADS-B) is a new surveillance system based on aircraft reporting of current position and velocity vector. ADS-B relies primarily on satellite navigation, which can be augmented by the Local Area Augmentation System (LAAS) and the Wide Area Augmentation System (WAAS). The improved navigation and surveillance accuracy of these systems have the potential to substantially improve surveillance accuracy over that possible with radar, thus reducing the effect of surveillance accuracy on spacing. In addition, the use of satellite position fixing can be used to substantially improve the accuracy of onboard aircraft navigation systems over that obtained using present ground-based navigation aids. In fact, the aircraft-to-aircraft separations that can be safely flown using modern navigation and surveillance systems are often considerably less than that permitted by wake vortex interference.

The FAA is in the process of defining a target level of safety for wake turbulence operations, which will be invaluable for developing effective safety cases and assessments (as defined in the FAA Safety Management System Manual and in FAA Order 8040.4 (FAA, 1998)) to support proposed operational changes. There is currently a lack of aviation community consensus on how to define an acceptable level of risk associated with aircraft operations in all wake vortex scenarios. Furthermore, there is little information available that would help quantify the number and severity of wake turbulence encounters before and after an operational change. The Aviation Safety Reporting System (ASRS) historically has not included wake turbulence encounters as a reportable event, except in reduced vertical separation minimums (RVSM) airspace at cruise altitudes. The FAA supported and funded a change to ASRS that provides for the limited collection of wake turbulence encounter information. The collection of data is limited to those airports where current procedural mitigation work is underway (Lambert-St. Louis International Airport [STL] and George Bush Intercontinental Airport [IAH]) and two of the airports where the A380 will initially operate (John F. Kennedy International Airport [JFK] and San Francisco International Airport [SFO]). Any further enhancement of the collection system is dependent on funding by the FAA.

Development of a safety case to support a procedural change is an arduous and costly process. The approval process has historically taken 2 to 5 years and requires extensive data collection and analyses, multiple simulations, and monitoring (Lang, 2007). Even when an effective, successful safety case is made, approval often comes in the form of a waiver from standard procedures. Such waivers are generally not applicable system-wide—they may be specific to an airport or even to a particular runway configuration. The approval processes for re-categorization of aircraft weight classes or the construction of new runways can be even more onerous.

There has never been an accident directly attributed to wake turbulence while aircraft were following IFR spacing criteria or the self-spacing criteria of AC 90-23F and the *Aeronautical Information Manual* in VMC. Current wake vortex separation criteria are conservative and sufficient for ensuring safe operations. The key question is: Can a reduction in wake vortex separation criteria be obtained while maintaining safety? The VMC spacing shown in Table 1-2 indicates that pilots will comfortably space more closely than the IMC standards allow, provided that they can see surrounding aircraft. In IMC the spacing could be reduced up to 1 nautical mile (NM), if new technologies or procedures can confirm the same level of safety and provide pilots and controllers with that same level of comfort.

WAKE TURBULENCE: A LONG POLE FOR CAPACITY?

Wake vortex limitations primarily restrict arrival capacity, and to a lesser extent, departure capacity. The degree of constraint will vary from airport to airport, based on diverse factors such as traffic mix, current capacity, runway configuration, and weather patterns. For the simplest case—reducing the spacing between two aircraft arriving on the same runway—various systems studies have estimated that the most viable concepts can yield roughly 5-15 percent extra capacity (Lunsford et al., 2005; Galpin et al., 2005; Rutishauser et al., 2003; Lebron, 1987). Although the reduced spacing increases capacity when it is available, it is available only when crosswinds are strong enough to sweep the wake vortices off the runway. For CSPA, however, the needed wind conditions are less restrictive, requiring only that the leading aircraft's wake will not be blown onto the follower's runway. Therefore, reduced spacing is permissible a larger percentage of the time. Accordingly, various studies have estimated the benefit of new CSPA procedures to range from 20 percent to over 50 percent (Lunsford et al., 2005; Lang et al., 2003, 2004, 2005; Lebron, 1987). At best, it would allow the two dependent runways to be decoupled, allowing them the capacity of two separate runways. It should be noted that increases in arrival will be more significant during IMC conditions, since VMC spacing is already more efficient. However, if these new procedures could prove the safety case that would allow a reduction of the minimum lateral runway spacing, airports could build new runways where there is sufficient space between present runways, thereby increasing capacity in all weather conditions.

For departures, it is estimated that 1 to 8 percent capacity could be gained on single runways (Lunsford et al., 2005) and about 10 to 15 percent on CSPRs, providing benefits of up to 23 percent for airports with a high proportion of large aircraft (Lang et al., 2003).

Some airports may not be able to take advantage of the extra capacity afforded by reduced wake turbulence spacing. Today's aviation system is a complex web of intertwined systems that constrain each other in ways that are not obvious. Runways, taxiways, gates, terminal traffic, emissions, and many other factors may limit capacity at a degree comparable to wake turbulence. Studies of tradeoffs at individual airports and at the systems level are useful in identifying the most fruitful areas for improvement. A JPDO systems study showed that a 3 to 7 percent decrease in wake vortex separation (depending on weather) reduced delays at SFO more significantly than did a 20 percent reduction in runway occupancy time (Borener, 2007). Furthermore, many existing capacity constraints will be eased or lifted as NextGen is implemented (JPDO, 2007). If wake vortex is not also addressed, other system improvements may not reach their full potentials.

Finally, capacity in and of itself is not always the best benchmark. If that were the case, NextGen goals could be achieved by constructing large airports far from population centers. Instead, capacity increases must occur where there is excess demand. In particular, urban airports with high demand and a limited amount of real estate could benefit from increased use of CSPRs. For an airport operating at 90 percent capacity, an increase in capacity of only 6 percent yields a 40 percent reduction in delays (O'Connor and Rutishauser, 2001). Furthermore, delays tend to propagate throughout the air transportation system; reducing delays at the busiest airports will increase the efficiency of the entire system.

Finding 1-1. Air transportation system capacity could be significantly enhanced by applying the results of robust and focused wake vortex research and development. These results will be required in order to use the system at its maximum efficiency.

Recommendation 1-1. Aircraft wake vortex characteristics of transport airplanes operating in the national airspace system should be assessed using the best standardized techniques prior to their introduction into service, so that appropriate separation criteria may be established with regard to each new aircraft model. The details of this assessment should vary based on the impact any new aircraft is expected to have on the system, with large and heavy aircraft receiving more emphasis than small ones in terms of data requirements.

STUDY PROCESS

As directed in the 2005 NASA Authorization Act (P.L. 109-155), NASA's Aeronautics Research Mission Directorate contracted with the National Research Council for an independent analysis of what should be the appropriate elements for a national approach to overcoming wake turbulence challenges. The committee's full statement of task is found in Appendix A.

The Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development Program (see Appendix B) first met for 3 days in April 2007. At that meeting, the committee received briefings from those who would be interested in the results of the study: NASA Headquarters, staff of the U.S. House of Representatives Committee on Science and Technology, and the JPDO. It also heard from many of the major stakeholders of the WakeNet USA forum: the FAA, NASA's Langley Research Center, the FAA's Volpe Transportation Center, MITRE, MIT Lincoln Laboratory, the Air Line Pilots Association, and the National Air Traffic Controllers Association.

At the second meeting, which took place in May 2007, the committee received briefings on European research from Eurocontrol and the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the current view of NextGen research from the U.S. Office of Management and Budget (OMB) and the Office of Science and Technology Policy (OSTP), and the state of the art in various wake turbulence technologies from a variety of experts in industry and academia.

The third and final meeting was held in July 2007. At that meeting the committee finalized the findings and recommendations contained in this report.

All three meetings took place in Washington, D.C. A full list of speakers is presented in Appendix C.

CHALLENGES

The committee began its work by listing the important challenges to address in wake turbulence. These challenges fell into two major categories: organizational challenges and technical challenges. A successful research plan would yield no gains in capacity or safety if the resulting solutions could not be implemented. Therefore, the two organizational challenges presented in Chapter 2 are equally important and are critical to the success of the nation's wake turbulence R&D enterprise. It was decided that the organizational challenges had to be overcome if the benefits of the technical challenges were to be realized. The technical challenges are presented in Chapter 3. Prioritization of the technical challenges and a complete program plan are presented in Chapter 4.

This report refers to short-, medium-, and long-term time frames. "Short term" is defined as activities carried out prior to 2012, "medium term," between 2012 and 2017, and "long term," 2017 to 2025. While the committee does not believe that the time frame carries any inherent priority, it does believe that the federal government should plan its research to sustain a continuous level of effort over time, and include efforts to realize the NextGen system. Some of these efforts may not reach their peaks before 2025, but large gains in capacity may potentially result.

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2

Organizational Challenges in Wake Turbulence Research

GET ORGANIZED

To best support a national approach to overcoming wake turbulence challenges, there needs to be a simple and clearly defined goal agreed to and understood by all participants. Based on current needs, an appropriate goal would be to develop the technical and procedural capabilities to increase capacity—without loss of safety—by reducing the required aircraft separation distances associated with wake turbulence avoidance. Efforts under a national approach must be defensible in the context of the goal; a solution cannot be implemented until there is justification for modifying the legacy rules, the pros and cons for the change have been analyzed, and the acceptability of new risk has been proven to those affected by it. In addition, when assessing the new procedures and developing the new technology necessary for the change, the ability of the air traffic control system and the airportals to handle the resulting increase in air traffic density must be considered.

With a goal in mind, it is possible to map out the development of the objectives and requirements for achieving that goal. The resulting roadmaps not only should guide federal wake turbulence research, but also should take into account the work of foreign agencies and universities, as well as relevant nonwake research performed by other entities to exploit synergistic work and identify potential partnerships. Gaps and duplication of effort should be avoided; investment requirements and milestones, risk mitigation, and acceptance or elimination processes should be understood; and stakeholders should be identified and acknowledged, including individuals who are accountable or responsible.

Currently, there is no coordinated support for wake turbulence research, nor is there an apparent champion, spokesperson, or leader held accountable for achieving the goals. Such a leader would be able to provide and defend a business plan that can accomplish the complex requirements of research, applied technologies, and procedural changes while demonstrating that the value of the endeavor is clear, even when compared to the many programs competing for the same limited funds. A recognized priority is a valuable asset for obtaining adequate and predictable funding and for protecting important programs in the face of budget cuts. The leader would help determine which federal government and civilian organizations or other resources are most appropriate and necessary for accomplishing the goal. He or she would be responsible for creating an effective and efficient program leadership structure. If multiple agencies or organizations are involved, the funding should have a common source rather than be contingent on the individual budgets of the participants. The leader should be highly respected and well known in his or her field and therefore able to attract and support the best research, technical, and operations personnel available.

Historically, NASA and the FAA shared leadership of wake turbulence research. This arrangement was successful when budgets were not so tight, but it is no longer feasible. While NASA has the technical expertise to support this leadership, wake turbulence research now lies outside its priority research funding focus. The FAA is responsible for the establishment of civil aviation safety standards and implementation of air transportation system changes, and therefore has an interest in all phenomena that affect safety, including wake turbulence. The JPDO has the ability to coordinate research, but as a planning agency it does not have the necessary executive power or budget authority. NOAA and DOD occasionally contribute to wake turbulence research, but their efforts are motivated by their own needs, not by the goal of increasing the capacity of the air transportation system. Without a leader, the alignment of these efforts depends on the relationships between individual researchers and on temporary partnerships between agencies. This is sufficient leadership to ensure success in projects and programs that take place over a few years, but not enough to tie those successes together into solutions.

Finding 2-1. There is no champion, spokesperson, or leader held accountable for goal achievement across the nation's wake turbulence research and development efforts.

Finding 2-2. Wake turbulence is a long-term problem. Although a total solution cannot be achieved within a decade, improvements will become available gradually, depending on funding, and it can be envisioned that these incremental improvements will provide incrementally increased capacity at airports where implemented.

Recommendation 2-1. Federal wake turbulence research should have the following characteristics:

- **The FAA should be the lead agency for defining requirements for wake turbulence research.**
- **The FAA should manage and fund capacity-focused wake turbulence research using academic, industry, and other government partners.**
- **The FAA should appoint a strong and motivated leader to integrate and coordinate research across agencies, define priorities, and represent wake vortex research to the JPDO and other agencies.**
- **Research should be sustained over the short, medium, and long term.**
- **Resource allocations across functional lines of involved agencies should be coordinated among all agencies involved in this work.**

Better coordination of the many independent entities that are currently studying wake turbulence characteristics, dynamic predictive capabilities, sensor and display development, and adaptive procedures will be important. Until recently, NASA provided essential fundamental wake turbulence research in partnership with the FAA. But budget constraints have severely limited NASA's ability to support the wake vortex research required for NextGen, creating a technology gap. While NASA is still well-aligned to do this research, in that it possesses the proper expertise, facilities, and institutional experience, it does not have the necessary resources. The FAA does not have this expertise, and there appears to be no other government agency with this capability or capacity. Other organizations with this technical capability will have to be identified so that the FAA can work with them.

Elements of a successful study of wake turbulence include (1) being identified as a major program within NextGen, the wide ranging transformation of the entire national air transportation system; (2) being included within the scope of one or more of the FAA Air Transportation Centers of Excellence; (3) being consolidated in a single location, perhaps at the FAA Field Office located at NASA's Langley Research Center, funded by the FAA; (4) being identified by the Administration as a high priority;

(5) being closely linked to all similar international studies; and (6) being identified as a high priority in the Aeronautics Research and Development Plan and the related Aeronautics Research, Development, Test, and Evaluation Infrastructure Plan, as it was in the NRC's 2006 *Decadal Survey of Civil Aeronautics*.

Finding 2-3. The change in aeronautics research priorities at NASA has led to a gap in the wake turbulence program as previously envisioned.

Finding 2-4. Present federal investment does not place sufficient priority on wake turbulence research to achieve the results called for by the NextGen goals.

Finding 2-5. NASA expertise is well-aligned to conducting medium- to long-term fundamental research, including wake vortex modeling and wake vortex alleviation work, while the FAA does not currently have such expertise.

Recommendation 2-2. Because of its expertise, NASA should continue to conduct medium- to long-term fundamental research, including wake vortex modeling and wake vortex alleviation work at a level of effort sufficient to achieve NextGen goals.

GET THE COMMUNITY TALKING

The wake turbulence issue and its relationship to a safe increase in airspace capacity spans a large number of disciplines—a community. Success with this endeavor specifically involves communication, coordination, and integration. To facilitate these elements, the implementing agency should begin in the earliest stages to involve representatives from all of the disciplines, ensuring that they have a common understanding of the task, agree with the goals and objectives, and are committed to support of the effort.

The goal of understanding wake vortices for the purpose of increasing airspace capacity has the greatest long-term impact on aircraft operators, including pilots, and the ATC providers. It would be wise to involve all of them as research is conducted on wake vortices so that they understand the methodology and that safety in our airspace will not be compromised as a result. At the same time, they can provide advice to the researchers on ways to make the change more useful to them, which will ultimately increase acceptance and adoption. The category "aircraft operators" is not limited to airline operations but also includes general aviation, military, and public service flight operations.

This community also includes the multiple elements of the JPDO in its effort to establish NextGen ATC operations. There are hundreds of initiatives and projects under the JPDO NextGen umbrella, and participants need a clear understanding of how potential wake turbulence solution set(s) interact with them. Many of these initiatives, such as navigation for approach and landing or departure, new runway construction, ATC and flight deck information display improvements, may interact technically with any wake turbulence solution. Priority for funding of these initiatives, including wake turbulence, can be considered in light of alternative project funding by weighing relative risks, benefits, and schedules. This would also allow wake turbulence and other initiatives to be fully integrated in terms of planning, technical and economic analysis, and budget execution. JPDO is not a direct recipient of program funds, but is a coordinating organization that develops plans for required work and that coordinates those requirements across agencies. Individual agencies submit their budgets for the work they will conduct. More detailed recommendations on budget are beyond the scope of this committee.

By getting the community talking in the earliest stages, there is increased likelihood of finding a practical and effective solution to the shortage of airspace capacity. Further, it is more likely that any spacing modification will be accepted because there will be reduced confusion, misunderstanding, and speculation over spacing changes. This challenge can be met if the agency that ultimately conducts the wake vortex research makes a strong and earnest outreach effort and maintains that communication throughout the research period. Communication can continue beyond the implementation phase in order to monitor the acceptance of spacing modifications and to provide data to end users showing the effect of research on the nation's airspace capacity.

Recommendation 2-3. Operators and controllers should be included in the process of designing, implementing, and evaluating wake turbulence-related changes to the air transportation system.

Recommendation 2-4. JPDO should recommend to the FAA detailed wake vortex research efforts needed to support NextGen.

3

Technical Challenges in Wake Turbulence Research

INTRODUCTION

There are two approaches to reducing the adverse impacts of wake turbulence on airport capacity while maintaining or enhancing the current level of safety. The ideal solution to the wake turbulence problem is to remove the threat by removing the wake. Although elimination of the vortex is physically impossible, it does appear possible to alleviate some of its effects. This requires innovative concepts that can be implemented on a significant number of aircraft. However, the benefits of vortex alleviation can only be realized in the long term, and even then, only if a particular concept proves viable.

If the threat cannot be eliminated, an improved spacing system can enable the next-best solution: Avoid the vortex or ensure that it can be tolerated. This requires gathering information about the position and strength of the vortex through some combination of monitoring and modeling. Using these data, separations can be safely reduced whenever the vortices have been carried away from the flight path or undergone sufficient breakup/decay. This solution will also require information about the local weather and its projected changes. The benefits of this approach are limited to specific atmospheric conditions, but can be realized immediately as they are implemented on an airport-by-airport basis without having to alter the aircraft fleet. A further enhancement to this type of solution is to provide the pilot with the information necessary to safely avoid nearby vortices. This could require altering the aircraft fleet to provide sensors, models, data display, local weather information, and information about the paths of preceding aircraft.

Advances to spacing systems and vortex alleviation will both require specialized research and technical advances in vortex modeling, vortex measurement, meteorological measurement, and vortex visualization. Supporting studies such as hazard boundary definition, system-level benefit studies, and the development of a system to gather data about wake events will be key to targeting research and eventually implementing solutions. Not only do they require the same supporting research, but alleviation and spacing also are not mutually exclusive—the best possible system may include elements of each. This section presents these technical challenges in more detail, along with relevant findings and recommendations.

First, however, a caveat: Because this report focuses on the wake vortex research needed for enabling capacity increases, approach and landing issues and, to a lesser extent, takeoff wake vortex issues were the main considerations. However, en route spacing reductions may also prove necessary to accommodate increased demand. The spectrum of aircraft to be commonly used in high-altitude jet flight will grow as the A380, at 1.25 million pounds maximum takeoff weight, is introduced at the high end, and “very light jets,” at perhaps as low as 6,000 pounds takeoff weight, are introduced at the low end. New safety challenges may also arise with the 1,000-ft minimum vertical spacing procedures recently adopted in many parts of the world for IFR operations. The FAA’s Web site contains more details: <www.faa.gov/about/office_org/headquarters_offices/ato/service_units/enroute/rvsm/>. The JPDO should not ignore these issues. Fortunately, most of the research challenges presented here may also be applicable to en route spacing.

Finding 3-1. En route wake vortex issues may arise, especially for very light jets in cruise.

Recommendation 3-1. The JPDO should investigate and define specific requirements for research on the impact of cruise-altitude-generated wakes on capacity (including climb and descent) to avoid future problems as fleet diversity increases.

IMPROVED SPACING SYSTEM DESIGN

Wake vortex considerations affect aircraft spacing standards for en route, approach and landing, arrival and departure. The FAA Research, Engineering and Development Advisory Committee’s (REDAC’s) Separation Standards Working Group (SSWG) found that “the current system, based on the separation standards that have evolved over the last 50 years, is safe, but still unable to meet projected demand. The separation standards (and the approach to establishing separation standards) now need to be reconsidered in order to meet the demand for increased capacity." Furthermore, it also found that "in considering the possibilities for reducing separation standards, wake turbulence becomes the driving consideration. For NGATS [NextGen], wake turbulence could become the primary limiter of capacity" (REDAC SSWG, 2006).

A four-dimensional, trajectory-based air traffic separation management system for arrival, departure, and en route conditions is a key component of the JPDO NextGen vision. This system would be based on precise trajectory and position information, including short-term intent data, and performance-based separation standards that account for aircraft capabilities, the local environment (e.g., wake vortex), and the encounter geometry. This system would include a substantial degree of automation (JPDO, 2007). While such a system is clearly critical to achieving NextGen capacity goals, it is not clear that any coordinated program exists to tackle the necessary research, particularly on wake turbulence.

Finding 3-2. NextGen is expected to include separation management capable of permitting reduced and dynamic separation standards.

Recommendation 3-2. JPDO should conduct a detailed analysis of what wake turbulence research and development is needed to achieve its separation management capability goals, and provide a detailed plan with milestones that will lead to successful development in the required time frame.

Air traffic spacing system design, combined with progress in other technical challenges such as hazard boundary definition, wake modeling, wake visualization, and wake alleviation (both active and passive), has the potential to offer capacity increases in the short term and in the long term. Some of these solutions may be dynamic—that is, spacing requirements are situationally dependent—but static solutions—that is, rule changes such as recategorization of aircraft classifications for spacing—can also provide benefit.

A simple example of a situationally dependent system is to allow spacing to be reduced when the vortices are being transported out of the next aircraft's path by the wind. Concepts that use crosswinds to enable closely spaced parallel approaches (CSPAs) and reduced separations on single-runway departures have been developed and tested at STL and IAH, respectively. Their operational implementation awaits approval of the safety cases, which is expected to occur soon (Lang, 2007). Currently, the FAA and NASA's Airspace System Program are conducting work on elements of these simple dynamic spacing system designs. Closely spaced parallel departures and single-runway arrivals may be considered as well, although a MITRE-NASA study found that procedure changes to CSPAs are generally more promising owing to their less-stringent crosswind requirements (Lunsford et al., 2005). In the medium term, the focus is on ATC data-driven procedural changes, such as static aircraft wake class recategorization. In the long term, the goal is to develop more complex dynamic spacing that depends on weather and/or traffic mix. The ultimate vision is to achieve active wake avoidance solutions, including a dynamic wake separation/dynamic wake class categorization. However, this ultimate vision is one of the topics that lacks sufficient investment to achieve the NextGen goals.

NASA's Aircraft Vortex Spacing System (AVOSS) project, conducted at Dallas/Fort Worth International Airport (DFW) in the late 1990s, provides a case study of the benefit that might be derived from reduced spacing, assuming that the airport is able to handle the additional capacity. This system used weather data to predict the behavior of a wake and the appropriate spacing for a following aircraft. The location of the wake was also measured with lidar. AVOSS was intended for research observations; it had no capability to affect aircraft spacing. However, comparisons between AVOSS's guidance and actual throughput showed that an operational version of AVOSS could have increased capacity by up to 16 percent, with an average of about 6 percent. Reduced spacing offers the most benefit to capacity-constrained airports; O'Connor and Rutishauser (2001) estimated that if DFW were at 90 percent capacity, a 6 percent increase in capacity would result in a 40 percent decrease in delays. In addition, since delays propagate through the air transportation system, a decrease in delays at large, capacity-constrained airports would echo across the system.

One of the major limits to the capacity enabled by such a system is its weather-dependency. Any dynamic wake vortex spacing criteria must be applicable a very high percentage of the time. Without this attribute, capacity gains will be offset by the inability to maintain schedule integrity when it is necessary to revert to today's wake vortex spacing separation standards.

Recategorization of some aircraft—changes to the weight boundaries for large, medium, and small classes, and perhaps also changes to the number of classes and the factor or factors that establish them—could reduce separation requirements in some operating circumstances. The development of procedures applicable to these specific types of operations may allow some capacity gains in the medium term. R&D has produced some capability to detect and track wake vortices in very localized areas. Achieving more substantial long-term capacity gains will require more effective wake vortex prediction, detection, and display capabilities, both on the ground and in the aircraft. In the long term, aircraft modification to alleviate the wake vortex threat may begin to generate even further capacity.

The European Commission has been pursuing very similar goals using a long-term, methodical procedure. It has already completed projects focused on encounter modeling (WAKENC), safety assessment (S-WAKE), and operational implementation (ATC-WAKE). The FAA and NASA are closely involved in the commission's current project, CREDOS, which examines the operational feasibility of wind-dependent separations for departure operations. Data from the STL tests are used for this project; the FAA has also made one of its lidar systems available to collect data at Frankfurt International Airport (EDDF). This is a strong, mutually beneficial partnership that will lead, it is hoped, to an International Civil Aviation Organization rule change that takes advantage of this work (Erikson, 2007).

Finding 3-3. Reducing the spacing needed to avoid wake turbulence will allow more efficient usage of existing runways.

Recommendation 3-3. The FAA, assisted by NASA, should continue its current improved spacing programs, which promise results in the short and medium terms.

In addition to allowing increased usage of existing runways in IMC conditions, dynamic spacing for CSPAs may eventually support a reduction in the current wake-vortex-related runway separation standards of 3,400 ft for independent approaches (spacing needs to be maintained only between aircraft on the same approach path) or 2,500 ft for dependent approaches (spacing must be maintained between aircraft on the same approach path and aircraft on adjacent approach paths). Reducing the required spacing of CSPAs will, in turn, allow construction of new runways between existing ones. Building new runways within existing airport boundaries will have less environmental impact than will expansion, resulting in a shorter, less expensive approval process. For airports whose borders may be constrained by geographical features (such as water or mountains) or heavy development, this is the only alternative to adding runways.

The FAA should continue these sorts of development efforts so that the minimum runway spacing can be determined for future airport expansions and the required suite of technology to support the reduced spacing can be established. These efforts will require system-level studies

TABLE 3-1 Milestones for Advanced Spacing System Design

Time Horizon	Milestone
Short term	Complete tests of conditional spacing reduction to closely spaced parallel approach (CSPA) at individual airports
Medium term	Allow conditional spacing reduction to CSPA at all selected airports Begin tests of conditional spacing reduction for single runway approaches Integrate reliable weather sensors into CSPA
Long term	Allow conditional spacing reduction to CSPA at all airports Allow conditional spacing reduction for single runway approaches at selected airports Begin tests of GPS-enabled, en route dynamic spacing

as well as simulator and flight experiments to gain acceptance by pilots, controllers, operators, and the FAA. Because it can take 10 years or longer to plan and design a new runway (GAO, 2003), it is imperative that this work start early in order for airport managers to understand their runway spacing requirements. Benefit studies performed in the short term can identify runway construction strategies capable of producing significant long-term gains in capacity. Paradoxically, such studies may allow identifying situations where runways should be aligned at an angle (instead of parallel) to the dominant wind direction, so that wakes can be more often transported away, increasing the percentage of time during which closer spacing could be permitted. Milestones for advanced spacing system design are shown in Table 3-1.

Finding 3-4. In many airports, the use of dynamic wake vortex spacing standards could permit parallel runways to be built closer together, meaning that in some cases, new runways may be built between existing runways, or elsewhere on existing airport property.

Recommendation 3-4. The FAA should pursue work in the short and medium terms to determine minimum runway spacing for future airport expansion, which is needed to achieve capacity goals in the long term.

VORTEX VISUALIZATION: COCKPIT AND CONTROLLER

Dynamic spacing of aircraft based on wake vortex motion will require prediction of wind behavior over roughly the next hour. It also will be necessary for the pilot and/or the controller to have information on the wake position in real time as a safety net to verify the predicted separation provided. The information could be presented to the pilot numerically, visually, or by a simple red-light/green-light system. One option for presenting the real-time wake position that has been researched is visualization. A visualization capability will give pilots and controllers better situational awareness, improving safety and allowing closer spacing. Ideally, real-time information on the position of the wake would be obtained by direct measurement. Near the ground, this may be possible to measure the position of the wake; however, it would be contingent on the development of all-weather sensors. Airborne sensors for measuring the wake of neighboring traffic are similarly unavailable. It is more likely that a real-time prediction model of the wake could be developed based on real-time traffic position broadcasts, aircraft characteristics, and measurements of environmental parameters such as wind and turbulence, supported by measurement of atmospheric and meteorological parameters.

Real-time prediction models yield large variations in the position of the wake behind an aircraft, although most of the variation is strongly dependent on parameters that potentially could be determined by sensors or other means. With sufficient modeling development along with the associated error bounds, this knowledge can be used to present the predicted wake hazard zone to pilots and controllers.

As discussed in the section "Wake Vortex Modeling," real-time models have been developed and are continually being refined. Hahn et al. (2004) applied real-time models for prediction of the wake danger zone, and Holforty (2003) compiled a model that predicted the wake location for a visualization flight test experiment. In addition, Ma and Zheng (1994) showed a real-time model and a method of presenting a three-dimensional visualization. A real-time model requires several parameters: the three-dimensional position of the wake-generating aircraft, air mass motion, and the characteristics of the wake-generating aircraft. The accuracy of the wake location prediction will depend primarily on the number and accuracy of the above parameters that are available for inputting to the real-time model. This model can determine the position in three dimensions of the wake danger zone for depiction by neighboring aircraft or air traffic controllers. The danger zone would be determined by projecting the hazard boundary onto the nominal wake location and accounting for any uncertainty. The size or existence of the danger zone would also depend on the relative size of the two aircraft. For example, a small, single-engine aircraft would not create a danger zone for an A380. (See below the section "Safety Analysis and Hazard Boundaries.")

Many factors could influence the vertical position of the wake danger zone. Specifically, if the vertical air mass motion and stratification are uncharacterized, they can move the wake up or down in a seemingly random fashion. There is also a large variation in the lifespan of a wake, depending on atmospheric turbulence (Crow, 1970). Due to the difficulty in obtaining all the parameters that affect these two dimensions of the wake location, the danger zone in these dimensions would be significantly larger than the nominal wake. On the other hand, there are fewer uncertainties in the lateral location of the wake.

The wake danger zone can be shown on a two-dimensional moving map display (Fiduccia, 2005). Most commercial aircraft now have a moving map display that could be used to display the wake danger zone associated with neighboring traffic within a certain altitude (e.g., 300 ft). This type of depiction might also be used on the radar displays used by ATC for all aircraft. ATC could then verify the safety of placing aircraft closer together in-trail when the predicted crosswinds indicate the safety of that separation. It would also enable ATC and pilots to verify the safety of more efficient spacing of aircraft on CSPAs (Powell et al., 2005). The wake danger zone can also be shown on a three-dimensional perspective display (synthetic vision), as shown by Holforty (2003).

The ability to predict and display the wake of a neighboring aircraft has been demonstrated in flight experiments (Holforty and Powell, 2003), and the predicted wake location was found to be identical to the actual wake position. In this case, the parameters of the target (wake-generating) aircraft were well known and the winds were known and steady, making the accuracy of the wake location prediction most likely better than could be expected under more typical conditions. However, the wake visualization concept was proven and was judged by the participants as superior to today's situation, where no information is available to pilots or controllers on the location of the wake.

The flight experiments and computer studies cited above were not exhaustive, nor were they applied to commercial aircraft. There needs to be more research into the most useful display methods; verification and development of the models with larger aircraft; addition of airborne atmospheric, meteorological, and wake detection sensors as they become available; thorough error analyses to determine the model accuracy and corresponding danger zones; and enough demonstrations to establish acceptance by all stakeholders: pilots, controllers, operators, and the FAA. If accepted by all, the results of the research could enable reduced separation of aircraft in all phases of flight, with a level of safety equal to or better than today's. This work would be most effectively conducted by a collaborative partnership between the FAA and NASA. Milestones for wake vortex visualization are listed in Table 3-2.

TABLE 3-2 Milestones for Wake Vortex Visualization

Time Horizon	Milestone
Short term	Review all real-time models and establish required measurements Establish error bounds for definition of wake danger zone Perform simulator studies of display options
Medium term	Use displays in simulator studies of CSPA procedures Flight test to validate depictions of the danger zone
Long term	Integrate airborne wake vortex sensors Certify sensors for use in ADS-B-equipped aircraft Use in flight test validation of CSPA procedures

Finding 3-5. Onboard wake vortex visualization has been demonstrated in a proof-of-concept trial and can provide a safety net for dynamic spacing procedures.

Recommendation 3-5. Wake vortex visualization concepts should be further explored and pursued.

VORTEX ALLEVIATION

Trailing vortices are an unavoidable consequence of finite-span lifting wings. The initial vortex strength scales with the aircraft weight and inversely with the aircraft wingspan. In general, vortex alleviation concepts aim at reducing the hazard posed by a vortex by altering the vortex's characteristics. This is done by modifying the configuration of the source aircraft. Any such modifications must not significantly degrade the overall aircraft performance or they will not be viable for integration on the aircraft. There have been many attempts over the last 40 years to evaluate systems that provide some alleviation of the wake vortices in laboratory simulations. These systems are reviewed by SavaĽ(2005) and Crouch (2005).

Vortex alleviation offers the potential to remove the vortex threat within a given distance of the generating aircraft. If successful, this solution would allow following aircraft to fly closer to the "vortex-alleviated" aircraft. The benefits of alleviation would be available at any airport used by the vortex-alleviated aircraft. Vortex alleviation benefits are also expected to be weather independent; they may be more fully exploited because they can be counted on and forecast well in advance. However, the total benefit of vortex alleviation to the national airspace system will be dependent on the number and mix of aircraft that have incorporated alleviation techniques. Thus, even if a vortex-alleviation solution is found, it will take many years before the benefits can be fully realized, depending on the general applicability of the concept.

The benefits of vortex alleviation can be measured by changes to the severity and the probability of vortex encounters. This requires measurements and/or predictions of the vortex characteristics as a function of distance behind the vortex-generating aircraft. Some form of vortex-encounter simulation can then be used to determine the potential severity of a vortex upset at a given distance behind the vortex-generating aircraft and to define the acceptable following distance enabled by each vortex alleviation concept. Implied in the assessment of vortex alleviation is a defined "hazard boundary" that can be used to judge if a given encounter is acceptable.

The approaches to vortex alleviation can be grouped into two broad categories, one aimed at vortex modification—that is, making vortices weaker or more diffuse—and the other aimed at vortex breakup—that is, forming vortex rings. Vortex modification is achieved through alterations to the loading of the wingspan (and sometimes the horizontal tail). Vortex breakup is achieved through unsteady forcing, preferably using standard control surfaces.

Vortex breakup relies on natural instabilities to amplify small vortex perturbations into large, wavy distortions of the vortices. The waviness ultimately leads to a periodic pinching of the vortices into vortex rings. The vortex rings undergo continued distortion, finally leading to a complete breakdown of the vortex system. The most promising way to accelerate vortex breakup relies on the multiple-vortex-pair system that can be generated by aircraft with their flaps deployed (Crouch et al., 2001; Crouch, 2005). This approach uses conventional control surfaces to excite rapidly growing instabilities that can break the vortices into rings within distances of approximately 3 NM for a "heavy" sized aircraft—significantly shorter than the aircraft separation distances imposed today under IFR. However, because this system relies on specific features of the initial aircraft wake, it is not expected to be applicable to all aircraft. Also, the allowable following distance may be somewhat greater than the distance to pinching, depending on the specific criteria used for its determination and the specific aircraft pair.

Some of the most promising approaches to vortex modification also make use of multiple-vortex-pair systems (Fabre et al., 2002; Durston et al., 2005; Savas, 2005). The addition of a strong vortex pair rotating counter to the basic wingtip vortices can lead to more diffuse vortices whose strength is the sum of the positive and negative vortices. However, the addition of the counter-rotating vortices costs aircraft performance. Even though it may dramatically alter the vortices, this approach does not look promising for implementation because of its effect on overall aircraft configuration.

Another approach that offers the potential for rapid distortion (breakup or pinching) of the vortices is to exploit transient growth or bypass mechanisms on the vortex or vortex pair (Pradeep and Hussain, 2006; Brion et al., 2007). Studies have shown significant alterations to the vortices, accelerating their decay, but the practical costs and value of this approach have not been assessed.

There is very little vortex alleviation activity in the United States with no discernible effort at any of the federal agencies. Activity over the past decade has been concentrated in industry, in academia, and in Europe. Research in this area requires innovative concepts (which cannot be forecasted) and fundamental investigations into the effectiveness and viability of the concepts. It is essential that the viability of concepts be assessed so that the limited resources can be focused on the most promising areas. Research on successful concepts should advance from computational fluid dynamics (CFD) studies, to experimental demonstrations and on to an assessment within the complexities of the real atmospheric environment. Progress toward alleviation also requires advances in the definition of a hazard boundary that can be used to judge the alleviation concepts and estimate their benefit. Milestones for vortex alleviation are shown in Table 3-3.

Finding 3-6. Vortex alleviation has the potential to significantly impact aircraft spacing requirements in the long term.

Recommendation 3-6. Vortex alleviation ideas, including configuration changes and active and passive forcing, should be explored.

Finding 3-7. NASA's aeronautics program is well-aligned to conduct wake vortex alleviation work as medium- to long-term foundational research.

TABLE 3-3 Milestones for Vortex Alleviation

Time Horizon	Milestone
Short term	High-level assessment of alleviation based on effectiveness and viability Multiple concepts explored Systems benefit studies conducted for best concepts
Medium term	Validation tests conducted for most viable concepts, at Reynolds numbers sufficient to represent an aircraft in flight, preferably via flight tests Assessment of performance under realistic atmospheric conditions for most viable concepts
Long term	Flight test conducted to demonstrate system effectiveness

WEATHER FORECASTING

Measurement of weather parameters relevant to wake vortex translation and decay is discussed in the next section. However, to ultimately take advantage of dynamic spacing, it will be necessary to be able to forecast the effects on wake vortices far enough into the future to allow spacing of arriving aircraft according to the conditions that will exist at their approach time. It does no good if the arrival queue has already been established in the terminal area according to existing spacing criteria when vortex and weather measurements reveal that the spacing could have been safely reduced.

To accomplish this, a local area forecast model of sufficient resolution will be required and the data to initialize it will need to be available. Existing forecast models have been used with some success at STL to forecast wake transport. A higher-resolution model will be required to improve on this and to forecast wake vortex decay. The Weather Research and Forecasting (WRF) model currently under development by NCAR, NOAA, DOD, the FAA, the University of Oklahoma, and others has the potential to meet this requirement in the necessary time frame. It is expected to be field tested in 2009 (Skamarock et al., 2007). Data from a scanning lidar could be sufficient for initialization of the model but would be available only in clear weather. Other means for data acquisition in inclement weather exist, but they might not be adequate for this purpose, for example, providing eddy dissipation rates (EDRs). EDR is a quantitative measure of ambient turbulence used in calculations of vortex transport and decay. However, by the time EDR is needed, data transmitted by aircraft in flight may be sufficient. Software to compute EDR is now onboard United Airlines aircraft and is expected to be operational on two other U.S. carriers by 2009. When ADS-B is operational, these data should be available in near-real time.

The WRF model will be capable of accepting data at sporadic intervals in time and space as they would be transmitted from aircraft. However, as of this writing, the model is still not capable of ingesting and processing EDR data, and no funding exists to develop this capability. Thus, although forecasts of conditions that would move wake vortices out of the areas of concern could be available in the needed time frame, forecasts of wake decay probably could not be achieved without further funding for model development.

European research has demonstrated some short-term forecast model capability at Frankfurt (Gerz, 2007). NASA and the FAA have been partners in this effort and are therefore presumably aware of its characteristics and potential. European as well as U.S. WRF development efforts can be monitored for possible future U.S. application. Milestones for weather forecasting are shown in Table 3-4.

TABLE 3-4 Milestones for Weather Forecasting

Time Horizon	Milestone
Short term	Coordinate needs with NCAR Investigate possible data inputs for weather models
Medium term	Test integration of data and modeling Incorporate aircraft-gathered data into model
Long term	Certify weather prediction procedures

Finding 3-8. The Weather Research and Forecasting model currently in development can provide the necessary weather prediction resolution to support the needs of NextGen. However, as presently conceived the model lacks the ability to incorporate eddy dissipation rates and thus will not provide the optimal set of parameters for predicting wake turbulence.

Recommendation 3-7. Federal wake turbulence research should engage the Weather Research and Forecasting model effort in order to identify the optimal set of weather parameters needed for predicting wake turbulence.

Finding 3-9. European forecast models have demonstrated some short-term terminal area wake vortex forecast capability.

Recommendation 3-8. Research should be done to ensure that weather modeling is adequate to predict wake vortex movement and decay.

WAKE VORTEX MODELING

The initial (near-field) wake generated by an aircraft can be extremely complex, while the far-field wake (at, say, 3 to 8 miles) is a relatively simple vortex pair characterized by a circulation strength, a vortex span (distance between the vortices), a vortex core size, and some measure of the long-wavelength vortex distortion. The characteristics of the far-field wake are strongly influenced by atmospheric conditions. The position of the wake far behind the aircraft depends on wind conditions and the integrated history of the wake characteristics. Wake vortex modeling attempts to predict the basic characteristics of the vortices from the near field into the far field as a function of the generating aircraft and the ambient atmospheric conditions.

Wake vortex modeling plays a critical role in many concepts aimed at reducing aircraft IFR spacing requirements. First, vortex models could be used to compare the relative vortex strengths of different aircraft at a given following distance. This information could be used in conjunction with some form of hazard boundary to reevaluate the aircraft weight categories on which aircraft spacing is based. Second, if models could be used (in conjunction with local weather information) to predict the vortex positions with sufficiently small uncertainties, they could be used to visualize the vortices from the ground or from the cockpit. Finally, vortex models could enable the use of dynamic spacing based on local weather conditions. The simplest application is to use the model to identify weather conditions in which vortex encounters can be completely avoided. Eventually, this could be extended to include weather conditions when vortices might be encountered but no longer pose a hazard. Different applications demand different levels of fidelity from the vortex models. Direct vortex measurement and detection can be used to supplement the vortex modeling for a dynamic spacing system, but the vortex models (in conjunction with local weather models) will determine how far in advance the airport capacity can be forecast.

Vortex modeling can be broken into two somewhat distinct stages in the vortex development: wake initialization (near-field development) and wake evolution (mid- and far-field development). The wake-initialization phase provides a link between the generating aircraft and the basic wake characteristics needed to model the wake into the far field. This phase is relatively short, so atmospheric effects are neglected. This phase is often simplified by assuming an elliptic span loading (for the total aircraft lift); this provides the basic wake characteristics as a function of the aircraft weight, span, and speed. It is a very rough approximation for configurations with flaps deployed. For some applications (e.g., predicting vortex positions), the associated errors may not be significant to the far-field estimates. However, any relative comparison of specific-aircraft wake strengths will likely be very sensitive to the wake-initialization phase. This could prove to be important for the characterization of different aircraft wakes in the far field.

The wake-evolution models start with a simple vortex pair and provide a time history for wake development as a function of atmospheric conditions. The essential wake parameters for this part of the modeling are the vortex strength and the vortex span. The key atmospheric factors are the background turbulence, the stratification, and the lateral shear. Ground proximity is another key factor that significantly alters the development and is often treated as a distinct module in the modeling. Wake-evolution models are highly empirical; their validity is strongly tied to the quality of the data used in their development. Therefore, the parameters used in the models are dictated by measurement capabilities and are not necessarily the most physically relevant. The stochastic nature of the atmospheric environment results in uncertainties in the model predictions; these uncertainties grow in time. They can overwhelm or amplify the uncertainties introduced with the wake-initialization model. Thus, any far-field predictions are probabilistic in nature, and this is specifically accounted for in some models.

To advance modeling of the wake-initialization phase, quality flight data are needed at distances greater than approximately 15 wingspans, but not so far downstream that atmospheric influences overwhelm the initial conditions. These data must be obtained under controlled conditions, where aircraft configuration details are varied and documented. The flight data could be supplemented with ground-based testing data if measurements are made sufficiently far downstream and the model represents a realistic aircraft configuration. These data can be used to assess current models or even to develop new models.

Modeling of the wake-initialization phase has not received much attention at any of the federal agencies. Recent efforts are focused in industry and in European agencies and universities. The state-of-the-art approach is to establish a wake survey at the tail of the aircraft using wind-tunnel experiments or full-configuration CFD and then evolve this downstream with a code that is optimized for calculating the wake development (Czech et al., 2005; Winckelmans et al., 2005). The current models have been tested against a limited set of wind-tunnel data, but no direct comparisons to flight data have been made.

To advance the prediction of wake evolution, the first challenge is to create probabilistic models that provide the nominal wake characteristics and the uncertainty associated with these values. These models can be used in conjunction with atmospheric measurements or predictions to predict the position of the wake as a function of time (or following distance). The combination of a probabilistic model and an atmospheric model can provide an "uncertainty box" around the predicted vortex positions that gives the range of possible positions within a given level of uncertainty. An indicator for how the uncertainty box grows with time as a function of different atmospheric conditions is needed to judge the utility of the predictions for a given application. The second challenge is understanding how the growth of uncertainties depends on the uncertainties in initial wake characteristics, and how this contributes to the scatter in typical flight data. Thus, current wake-evolution models would also benefit from quality flight data that could permit accurate initialization of the wake and permit comparison in the far field. The third challenge is estimating the overall confidence in the model under different conditions to assess when the models could be used and when real-time wake detection would be required. Additional flight data will be required to advance the development of wake-evolution models. These data are needed to isolate and model distinct atmospheric influences. Wake-evolution models may also benefit from more fundamental research on the effects of wind shear and atmospheric turbulence. Turbulence from the aircraft wake and the ambient environment can trigger vortex-core instabilities and bending waves (Melander and Hussain, 1993), in addition to long-wavelength vortex pair instabilities (Crow, 1970).

Modeling of the wake-evolution phase has been ongoing at NASA Langley Research Center, with research assistance from the Naval Postgraduate School and Northwest Research Associates. Real-time wake prediction models have been developed based on numerical models and validated with empirical data (Robins and Delisi, 2002). These real-time models use meteorological sensors to predict the movement and decay of the wake vortices and wake vortex measurement sensors to verify the results. Real-time models show the most promise for use in an operational environment because the codes are so efficient. Before real-time models can be used in air traffic management systems, they must be thoroughly validated. NASA's AVOSS project, discussed above, used lidar to verify the predictions of its real-time model (O'Connor and Rutishauser, 2001). The NASA AVOSS Prediction Algorithm Model is a deterministic model (Proctor, 2007) based on the models of Sarpkaya (2000) and Greene (1986). A probabilistic version of the AVOSS model is under development (Proctor, 2007). Two well-known probabilistic models have been developed in Europe, the P2P model (Holzapfel, 2003) and the P-VFS model, which is based on the deterministic model VFS (Winckelmans et al., 2004). Milestones for wake vortex modeling are shown in Table 3-5.

Finding 3-10. Wake vortex modeling is an essential element for most concepts aimed at reducing IFR spacing requirements.

Finding 3-11. NASA's aeronautics program is well-aligned to conduct medium- to long-term foundational wake vortex modeling.

TABLE 3-5 Milestones for Wake Vortex Modeling

Time Horizon	Milestone
Short term	Flight test requirements defined based on modeling needs Probabilistic model developed based on the state of the art Vortex uncertainties predicted for different weather conditions
Medium term	Flight test conducted (as necessary) to support/validate modeling Wake models evaluated using flight data Range of applicability estimated for models Models applied to support recategorization efforts
Long term	Models applied to support dynamic spacing system

WAKE VORTEX MEASUREMENT

Sensor technologies have contributed to the continued advancement of knowledge in wake vortex research since 1970 (Burnham, 1977). The role of these measurement systems has evolved as the technology capabilities advance to higher resolutions and longer ranges. For instance, some sensors are used to measure aircraft wake vortices, and others are used to measure the meteorological conditions for inputs into the wake vortex and weather prediction models. In addition, there are two fundamental roles that wake measurement systems serve:

- Sensors for real-time models are required to detect the presence of aircraft-generated vortices in a volume of interest, typically in the approach or departure corridor.
- High-resolution wake measurements are required to make high-resolution measurement of the velocity field sufficient to validate robust wake vortex models.

The various sensing systems developed over the years have made a significant impact on wake vortex modeling and provided a better understanding of wake vortex behavior. Current state-of-the-art sensor technologies do not provide sufficiently detailed measurements of the three-dimensional aerodynamic phenomena needed by wake vortex modeling to advance the understanding of vortex behavior, and they cover only the landing and takeoff operations below 1 kilometer of aircraft altitude. Furthermore, the benchmark for wake sensors is an electro-optical system that works only in visual meteorological conditions. Although much progress has been made, there is still a need for higher resolution, higher spatial coverage, and all-weather capabilities. Other operational considerations include autonomous operation, real-time processing, all-weather performance, and cost (Burnham, 1997).

The main challenges for the development of a sensor for real-time models are system reliability, all-weather operation, and spatial coverage. Because most wake vortex sensor systems were developed for research applications, continuous reliable operation was not an important design driver. From now on, however, system reliability will be a major design requirement since the eventual installation will be operating in the national airspace system. The second major challenge is the ability of the sensor system to operate in all weather conditions. Lidar systems are optical sensors that perform as long as the transmission of the laser is not interrupted. They have become the sensor of choice for measuring wake vortices, but they are unable to produce a better understanding of wake vortex behavior in all weather conditions, as required by an operational system. The third challenge is to provide real-time detection of wake vortices and to monitor meteorological conditions along the flight path. Measured atmospheric parameters for locations along the flight path would improve the accuracy of a real-time wake vortex prediction system. If all of these challenges can be successfully overcome, they could contribute to the long-term vision whereby each aircraft acts as a sensor, providing data to a networked, high-resolution atmospheric monitoring network. While lidar systems are impractical for this purpose (they can detect wakes perpendicular to their line of sight but not parallel to it), if a suitable wake measurement concept became available, it could be added to an aircraft's suite of sensors. Through some combination of modeling and monitoring, the aircraft would then be able to determine the location of its own wake, which could be added to the ADS-B information stream. Alternatively, an airborne sensor on each aircraft that measures the location of the wake of nearby traffic might be possible, eliminating the need for transmitting the information via ADS-B. This capability is related to a challenge discussed above in the section "Vortex Visualization: Cockpit and Controller."

Higher-resolution measurements would support the development of large eddy simulation (LES) of wake vortices and provide wake vortex modelers with the empirical data they need to validate their computational models. Laser Doppler velocimetry—pulsed coherent and continuous wave lidar—systems are able to detect and measure wake vortex characteristics from the ground. Other sensor systems such as radar acoustic sounding systems, monostatic acoustic vortex sensing systems, and windline anemometers have also demonstrated their capabilities. The measurement challenge is twofold. The first challenge is establishing the resolution requirements, which will require a collaborative effort between wake vortex modelers and sensor developers to avoid the ambiguities often associated with the research area. The second is developing a sensor that can make high-resolution measurements in the volume of interest. For takeoff and landing, most of the volume of interest is beyond the range of the higher-resolution continuous wave lidar. Other sensors are within range but unable to provide adequate data resolution.

Wake vortex measurement systems have been developed with different principles of operation that take advantage of the particular meteorological conditions in which they are designed to operate. Lidar sensors are electro-optical sensors that work best when the weather is clear. The principle of operation for lidar is measuring the backscatter of laser light from the particulates trapped in the vortices. Acoustic systems use acoustic pulse to backscatter the vortex Doppler-shifted acoustic energy from the density variations in the vortices. Early wake vortex radar designs and simulations showed that water droplets trapped in the vortices would provide sufficient radar backscatter to detect and measure the vortices in inclement weather. It would be very difficult to develop an all-weather sensor because the sensing principles vary for different weather conditions and are limited to the signal propagation capabilities of the particular sensors. It is more reasonable to develop an all-weather system that includes multiple sensors. A lidar sensor can operate when the weather conditions are suited for its operation (e.g., visual meteorological conditions); when the weather conditions are better suited for an electro-magnetic sensor that can penetrate and use the scattering properties of water droplets (e.g., instrument meteorological conditions such as rain, fog, and snow), a multisensor system can switch over to the most effective sensor. A multisensor systems approach would also be cost-effective, because to date, no single sensor has shown that it can provide detailed and reliable measurement of the wake vortices. Furthermore, the knowledge gained from the lidar sensor system can be used to advance the technology in the new inclement weather wake sensor.

Wake vortex modelers can benefit from empirical data that can lead to the development of a validated wake decay model. Knowledge of how atmospheric turbulence influences the rate of wake vortex decay is as important as knowledge of how vortices are transported by the winds. The challenges include developing not only a validated wake decay model, but also technologies for measuring the volume of interest in takeoffs, cruise, and landings. Milestones for wake vortex measurement are shown in Table 3-6.

Finding 3-12. Research and development of high-resolution wake vortex measurement sensors to support wake vortex modeling efforts has stalled since the late 1990s.

TABLE 3-6 Milestones for Wake Vortex Measurement

Time Horizon	Milestone
Short term	Complete feasibility studies to develop high-resolution, all-weather wake vortex measurement system Develop functional requirements that are consistent with wake vortex modeling needs
Medium term	All-weather wake vortex measurement system Airborne wake vortex sensor Wake vortex measurement network
Long term	High-resolution, all-weather wake vortex measurement system High-resolution, all-weather wake vortex measurement network

Finding 3-13. No high-resolution wake vortex measurement system capable of operating in inclement weather exists.

Recommendation 3-9. Explore concepts for an all-weather, aircraft-based wake vortex measurement system that provides information on the location of the wake.

Recommendation 3-10. Develop an all-weather wake vortex measurement system that provides high-resolution measurements of wake vortex characteristics sufficient to validate wake vortex modeling.

SAFETY ANALYSIS AND HAZARD BOUNDARIES

While in a perfect world means would be sought to avoid any wake vortex encounters, such avoidance is simply not possible, nor is it necessary for safety. A hazard boundary provides a demarcation between acceptable and unacceptable vortex encounters based on criteria developed in conjunction with the pilot community. The maximum aircraft bank angle resulting from an encounter is the most common metric for characterizing the severity of an upset. An example of a simplified hazard boundary would be the level of maximum bank angle that would result in a given percentage of pilots executing a go-around. The definition of hazard boundaries, along with development of an end-to-end safety analysis methodology, is critical to any new system that is not based completely on avoidance.

Finding 3-14. Although the current air transportation system was designed to avoid wake vortex encounters, they do occur and are safely tolerated using present spacing criteria.

Finding 3-15. It is difficult to quantify acceptable reductions in wake turbulence spacing because there is no agreed metric for, nor definition of, hazard boundaries for wake encounters.

Recommendation 3-11. A hazard boundary needs to be defined and used as a metric in forming spacing criteria.

A rigorous safety analysis methodology is important for assessing the relative benefits of various mitigation solutions and for decision making in real time. The necessary elements of this methodology include (1) quantification of the uncertainties in wake prediction, aircraft characteristics, and local weather prediction; (2) assessment of how these uncertainties translate into a corresponding risk assessment; (3) the definition of an acceptable level of risk and a corresponding definition of what constitutes a wake-turbulence hazard; and (4) a procedure for real-time decision making under uncertainty—for example, to determine dynamic spacing of aircraft.

Strategies implemented to reduce the capacity constraints brought about by wake turbulence must not compromise safety. Concepts such as dynamic aircraft spacing, which have been proposed as long-term solutions to achieve NextGen capacity goals, clearly require explicit definitions of hazard boundaries and acceptable levels of risk. This requirement takes on more importance as the fleet mix comes to include a larger range of aircraft sizes—for example, VLJ and A380 aircraft—that move beyond the current size categories on which spacing is based. Hazard boundaries also play a role in evaluating proposed concepts for wake vortex alleviation.

Previous work of this nature has been carried out as part of the European S-Wake program under the Vortex Encounter Severity Assessment (VESA). VESA is a software tool developed by Airbus that estimates the probability of exceeding certain hazard levels given encounter conditions such as vortex characteristics, encounter geometry, and weather (Höhne, 2004). Ongoing work is addressing the validation of VESA based on flight test data. VESA is currently used in CREDOS, which is pursuing (with FAA and NASA participation) the development of crosswind reduced separations for departure. VESA is also used for safety assessment in the FLYSAFE and VITA projects, where parts of VESA are used to assess the severity of wakes.

The challenge of hazard boundary definition is not being addressed by current research in the United States, but it must be addressed if the NextGen vision is to be achieved. The activities needed range from methodological and vehicle-level research to more operationally focused determination of standards. This work would be most effectively conducted by a partnership between NASA and the FAA. Because defining a hazard standard is ultimately the responsibility of regulatory bodies, it should be led by the FAA. However, substantial research at the aircraft vehicle level is also required. For example, well-designed simulator studies are needed to characterize an acceptable wake encounter and to identify appropriate metrics for defining the hazard boundaries. This aspect of the work could be led by NASA, using contract support from aircraft manufacturers, airlines, and pilots. The effort should build on work from VESA and include carefully constructed simulator studies using "naïve" airline pilots as well as representatives from the business and general aviation sectors. It is important that the study provide typical pilot reaction to unexpected encounters, and that the pilot subjects not be permitted more than a few encounters, so as to minimize learning. A wide range of typical aircraft

TABLE 3-7 Milestones for Safety Analysis and Hazard Boundaries

Time Horizon	Milestone
Short term	Identify metrics for hazard definition Review European studies and complete detailed plan for simulator studies Begin conducting simulator studies Identify conservative hazard boundary
Medium term	Analyze results from simulator studies to quantify hazard Develop risk assessment methodology and apply it to simulator studies Refine hazard boundary based on available data
Long term	Test and implement refined hazard boundary Demonstrate real-time safety analysis in actual flight

encounters must be explored, so that the envelope of the boundary can be reasonably defined with respect to leader and follower aircraft size and wake strength at encounter. The development of simulator software that could be shared with a number of airlines for use during their pilot training programs would be one way to acquire useful data over a wide range of encounter situations. At the same time, research is needed to develop a methodology for probabilistic safety analysis. This is an important component that NASA could lead. Milestones for safety analysis and hazard boundaries are shown in Table 3-7.

SYSTEMS TO GATHER DATA ABOUT WAKE EVENTS

The challenge described here is to develop a means of collecting information from wake events that have actually occurred, as observed and reported by pilots. Currently only a very limited amount of information on a wake event is collected in any form by any agency in the United States, so that baseline data are not readily available. Without an event-driven database as a control, it will be very difficult to measure whether any future increase or decrease in wake events is the result of reduced spacing or is simply in line with current event levels.

Pilots and controllers today do not have a simple system for reporting the impact of a wake event in all phases of flight. The only wake reporting aid is the Supplemental Form, which must be attached to the NASA Aviation Safety Reporting System (ASRS) general form. The Type of Event/Situation section of the NASA general form (NASA, 1994) must be completed with the annotation, "Wake Turbulence." The Supplemental Form is used only to report the reduced vertical separation minimums (RVSMs) in domestic airspace between 29,000 ft through 41,000 ft (flight levels 290-410.) This limitation does not allow for reporting an event at lower altitudes, on arrival, approach, or departure. The FAA has funded a modification for the ASRS reporting system that would include wake encounters at lower altitudes but only on an official basis for those airports where current procedural mitigation work is under way (STL and IAH) and those airports where the A380 will operate (JFK and SFO). Many pilots are independently using the ASRS format to report wake encounters at altitudes other than those specified, but there needs to be a concerted effort to modify the system to officially collect the data from as many aircraft, in all flight phases, as possible.

Establishing this baseline would accomplish several objectives. It would allow researchers to measure any future change in the number of events as a result of reduced aircraft spacing against the number of events given current aircraft spacing procedures. It would also begin an involvement with U.S. pilots and controllers at an early phase of research on the wake turbulence issue. This participation and communication will be crucial in gaining acceptance of any spacing modification as a result of the total wake turbulence research effort. Additionally, data collected in this effort could be utilized in establishing agreed-on metrics for defining hazard boundaries for the wake encounters. It will be important that data be collected for all phases of flight (departure, climb, cruise, descent, and approach) and that they reflect as many categories of aircraft as possible, from the A380 through light general-aviation aircraft.

The ideal methodology for this effort should include data from both the leading and the trailing aircraft in an event. There are many parameters that would need to be identified in order to compile accurate and sufficient data, including aircraft types, altitudes, airspeeds, weights, and meteorological data, including temperature, wind direction, and velocity. Additionally, the location of the trailing aircraft relative to the leading aircraft must be known as accurately as possible. While the data might be readily available, their collection could prove to be rather problematic. Current-generation transport aircraft, including corporate and business aircraft, are equipped such that crew members could report most, if not all, of the data required. Flight data recorders could further provide information on any vertical acceleration and/or any change in attitude as a result of the event. Acquisition of the data from U.S.-certificated aircraft and crews will be the biggest challenge in this project. Any emphasis on reporting of events would undoubtedly increase the number of reports over the current level. Media interest in this higher number could cause both operators and manufacturers to become concerned about the liability, threatening the viability of a data acquisition program at its very outset. Therefore, a process for de-identification of data and restricted access to it would have to be in place before the start of the reporting. Even without access to information from flight data recorders, significant benefit could accrue from basic pilot reporting of a wake turbulence event. Any human-based wake reporting system will have to take into account human factors and the added workload. These factors will greatly affect the willingness to submit such data and their accuracy.

Depending on the level of the data eventually obtained by this methodology, they could be used to correlate the operator input with detailed research data obtained from other elements of future wake turbulence research in the United States.

Finding 3-16. Implementing a system to gather data on wake events in the short term could establish a baseline that could be used to quantitatively evaluate potential solutions, as well as gain the support from the operator and ATC community that will be necessary to increase system capacity.

While the challenges of this data collection might sound ominous, there is precedent in the United States for such extracurricular reporting. In December 2004, the FAA issued an advisory circular (FAA, 2004) establishing a methodology for reporting wildlife–aircraft strikes. The FAA, in cooperation with the Smithsonian Institution, gave pilots, maintenance personnel, and ground personnel detailed instructions for reporting a wildlife–aircraft strike; the methodology included transportation of bird feathers to the Smithsonian's feather identification laboratory in Washington, D.C. The FAA worked with the U.S. Air Force and the U.S. Department of Agriculture to improve the understanding and prevention of bird strike hazards. Through this program, the FAA maintains the National Wildlife Aircraft Strike Database and provides a very detailed form (FAA, 2006) for reporting such events that could serve as a model for reporting a wake turbulence event.

Either the FAA or NASA could, if so directed, institute a wake turbulence event reporting system. The FAA effort could be an extension of the bird strike reporting activity, while the NASA effort would be an extension of the ASRS activity. Given the concerns about liability mentioned above, it is useful that the ASRS already has de-identification and protection for reporting personnel. Flight personnel are already reporting to NASA without fear of enforcement action or liability. The question of access to flight data recorder information would remain problematic regardless of which agency was collecting the data.

The plan for data collection would have three phases:

- *Phase One*—A wake turbulence encounter database could be established. During this ramp-up phase, the aviation community would be advised that a database was being established and reporting would be encouraged. At the same time both written and electronic means of reporting the encounter would be developed. FAA air traffic controllers would be an important part of the data collection and therefore be included in the communication effort. For example, if the pilot of a trailing aircraft reported the encounter, the controller handling the flights would need to determine the data for the leading aircraft that could be generating the wake vortices. The research agency would establish a protocol for any follow-up (if required) to the initial report with both flight crew and controllers. In this phase of the program, the data collected could be used to develop flight simulator models of realistic wake vortex encounters. These models would be installed in the flight simulators of airlines and other commercial entities to better define hazard boundaries. Such scenarios would not only provide wake vortex encounter training for pilots, but could also be a real-life source of information to assist in defining hazard boundary metrics. This phase could be initiated in the short term.

- *Phase Two*—Data could continue to be collected and analyzed. Efforts could be started to reach agreement on access to flight data recorder information to supplement the basic report filed by pilots and controllers. Flight training and evaluation could continue. Input from line pilots to help in defining the hazard boundary could be gathered and analyzed. Because the issue of access to the flight data recorder arises at this point, Phase Two will probably not be attainable until the medium- to long-term time frame.
- *Phase Three*—As any modifications to the separation requirements are implemented, the agency could then compare event frequency and impact data with similar data gathered before the separation requirements were modified. If any degradation of safety were detected, separation requirements could be modified accordingly. Flight simulator training for wake vortex encounters could become part of a pilot's initial and recurrent training and could be modified in concert with any advances or changes in wake turbulence alleviation. This phase could become an ongoing program much as the ASRS program is today.

On the international scene, input from pilots and controllers on wake encounter events was being collected and processed on a very limited basis at London Heathrow airport (Critchley and Foot, 1991) as part of a larger, ongoing data collection effort in the United Kingdom. A sample wake turbulence encounter report form is reproduced in Appendix E. Milestones for systems to gather data about wake events are listed in Table 3-8.

TABLE 3-8 Milestones for Systems to Gather Data About Wake Events

Time Horizon	Milestone
Short term	Undertake outreach efforts to aviation community Task data collection agency Establish reporting protocol Initiate reporting system and begin gathering data Interface with hazard definition effort
Medium term	Get agreement between operators and controllers on availability of flight recorder data Analyze reported data that will assist in safety analysis and determining hazard boundaries
Long term	Implement data-gathering system to evaluate changes to separation standards, such as from dynamic spacing systems and wake vortex alleviation Integrate wake vortex response into pilot training and modify it as required based on data analysis

SYSTEM-LEVEL STUDY OF BENEFITS

System-level studies are required to assess the relative benefits of wake turbulence mitigation strategies and to help with setting research priorities and using resources effectively. It is important that system-level studies cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts. For example, identifying the potential benefits of reduced aircraft spacings in different operational settings requires first determining the relative impact of different options that may be applicable only at certain airports or under certain weather conditions. A number of potential improvements in wake vortex separation efficiency could be realized in the short and medium term that have been identified by the FAA. For reasons of airport geometry, terrain, fleet mix, or a combination of such factors, some of these improvements are applicable only to unique airport situations. Other wake vortex solutions are applicable to a particular set of airports or runway configurations, such as parallel staggered runways, parallel nonstaggered runways, and intersecting runways. These differences can become important, since (all other things being equal) solutions applicable to unique airport configurations have less overall potential for benefit than those applicable to a class of many airports, or those applicable generally.

Another important aspect of system-level studies is to identify when and which other constraints in the system become active as the wake constraints are modified. As discussed in Chapter 1, the aviation system is a complex system with multiple factors affecting system capacity. To realize the full benefits of strategies for mitigating wake-turbulence constraints, these other factors must be studied and assessed.

Research to address this challenge is being carried out by the JPDO Evaluation and Analysis Division (Borener, 2007). For example, a constraints analysis has been carried out to examine and quantify the primary factors limiting system performance. This analysis is being used to identify and quantify the long-pole factor(s), as well as to inform agency research and development plans to focus on key areas to help achieve NextGen goals. Ultimately the goal is to consider capacity, environment, safety, security, and costs, although initial analysis has been limited to capacity and environment. Another example is a study conducted to determine whether runway occupancy time or in-trail separation on final approach due to wake vortex constraints is the most binding constraint on capacity for SFO. The Ventana NextGen Portfolio Simulator is a quantitative framework that takes performance estimates from these kinds of more detailed simulations and links them with a heuristic model to estimate the aggregate result of NextGen investments on system performance. Specifically, the tool is used to explore R&D portfolio design by quantifying how R&D leads to changes in the system performance over time as NextGen is implemented (Goldner and Borener, 2006).

NASA Ames is pursuing development of the Airspace Concept Evaluation System (ACES) (Couluris et al., 2002; Sweet et al., 2002; NASA, 2005), a modeling and simulation environment for the national airspace system. ACES is intended to enable comprehensive assessment of the impact of new tools, concepts, and architectures. It covers aircraft flight from gate departure to arrival. The ACES environment is constructed so as to be flexible and extendable; that is, it supports plug-and-play assembly of different models.

The program required to address this challenge would encompass both technical research to further develop the detailed simulation models described above and research that is more oriented to organization and management to tie quantitative studies to research prioritization processes.

Large-scale simulation and optimization methods play an important role in providing means to carry out system-level studies. The aviation system is extremely complex and has many uncertainties. Simulating the entire system at the level of detail required to assess the relative benefits of technological and operational solutions is a major challenge for the software development and modeling community. This challenge is described in Hunter et al. (2005) along with high-level requirements, architecture considerations, and software development strategies. The ongoing NASA and JPDO efforts described above have gone some way to addressing this challenge; continued focus, integration, and coordination in this area are essential.

TABLE 3-9 Milestones for System-Level Study of Benefits

Time Horizon	Milestone
Short term	Simulation capabilities for arrival/departure operations extended to cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts
Medium term	Fleetwide simulation capabilities for gate-to-gate operations
Long term	System-level simulation capability that includes the effects of uncertainty, to support dynamic spacing system design

The system-level studies presented to the committee and documented in the literature have been for the most part limited to studies at specific airports (e.g., the runway occupancy versus in-trail separation study was done at SFO). The challenge is so important that resources need to be directed toward extending simulation capabilities to cover a range of operational and weather scenarios, fleet mixes, and airport layouts. Milestones for system-level study of benefits are shown in Table 3-9.

Finding 3-17. System-level studies are an essential element of a wake turbulence research program. They are basic to ensuring that (1) research priorities will be set in a rational manner, (2) the actual realizable benefits of wake turbulence solutions will be known, (3) key constraints can be identified, and (4) NextGen capacity goals can be achieved.

Recommendation 3-12. The current JPDO research in system-level modeling of the air transportation system should be continued and resources should be directed to extending simulation capabilities to cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts.

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4

Wake Turbulence Program Plan

PRIORITIZATION OF CHALLENGES

In addition to identifying the challenges described in Chapter 3, the committee was also charged with prioritizing these challenges and generating a draft program plan. The committee found that the challenges were highly synergistic, which made it very difficult to prioritize them as a single list; a particular challenge's ability to provide capacity was generally linked to the accomplishment of other challenges and thus contingent on the contents of the total research portfolio.

The committee therefore decided to roll prioritization and program planning into a single step. In Figure 4-1, each challenge is accompanied by a bar stretching from the short term to the long term. The height of the bar represents the level of effort recommended by the committee; the shading of the bar represents its priority. Levels of effort are approximate and meant to show the relative changes of activity within that challenge and which challenges are emphasized during each time frame.

The utility of a prioritized list is that, in the absence of a sufficient budget, a program manager may decide to cut the lowest-priority items. Given additional resources, he or she may decide to allot them to the highest-priority challenge. The system shown in Figure 4-1 suggests a different approach. Because of the interrelationships among the challenges, instead of cutting or eliminating one challenge, levels of effort should be lowered across the board, with medium-priority challenges taking a slightly larger cut than high-priority challenges. The committee did not judge any of the challenges to be of low priority. In this way, the time

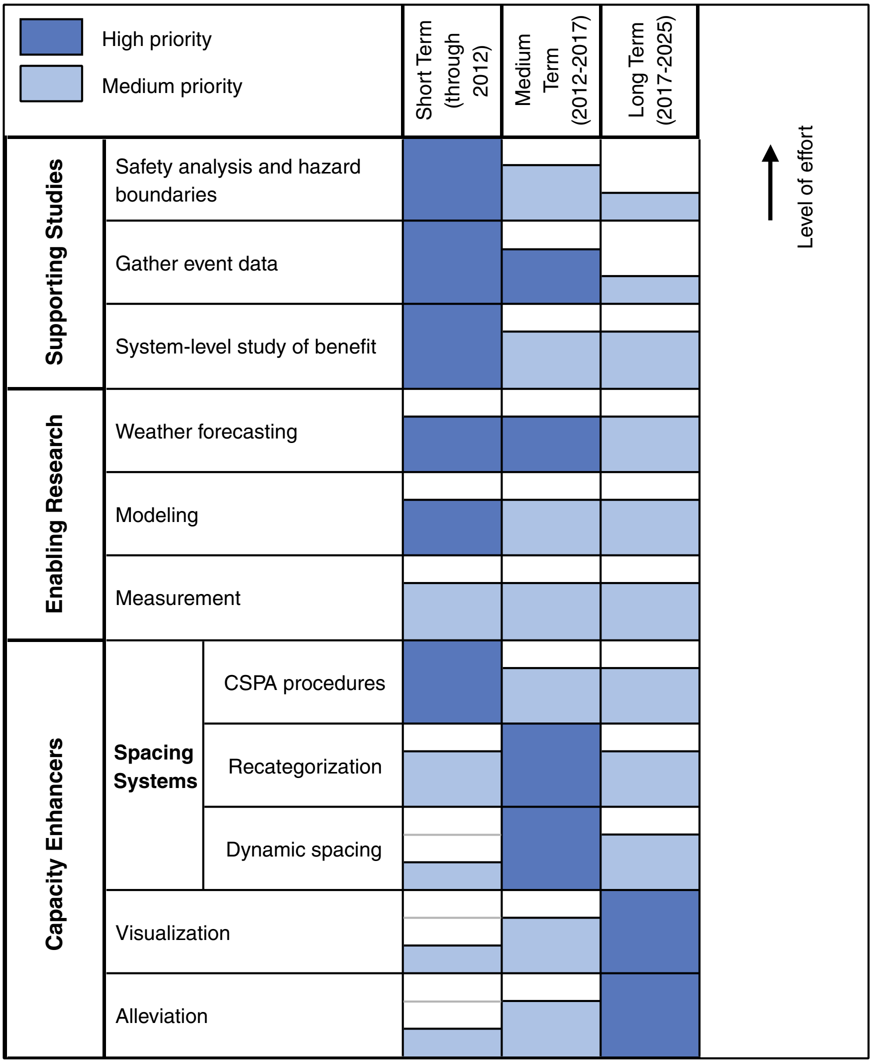

FIGURE 4-1 Recommended priority and level of effort for wake turbulence challenges. Height of each bar indicates level of effort. Shade of each bar represents priority (darker corresponds to higher priority). CSPA, closely spaced parallel approach.

horizon of the program may grow longer, but the quality of the results will not be jeopardized. Similarly, if more money becomes available, it should be used to bolster all of the efforts. The priorities and levels of effort were selected to give the program as a whole the greatest potential to create capacity.

Supporting studies are high priority and merit high levels of effort in the short term. All of these studies will be of great value in characterizing and evaluating potential solutions, so creating them and putting them in place quickly will maximize their value. Once models have been created, hazard boundaries have been set, and reporting systems are in place, much less work will be needed to maintain and make use of these capabilities.

Capacity enhancers are focused projects that address specific changes to the air transportation system. Each follows the same general pattern: At the start, there is a low level of effort associated with performing studies of tradeoffs and evaluating potential concepts. As concepts are narrowed down, effort is ramped up, culminating in a testing effort. If the technology is accepted, a smaller level of research will continue to assist in certification and handoff to the operational side of the FAA. Federal research should be addressing multiple capacity enhancers at various levels of effort at any given time. This allows sufficient sharing of resources such as lidar systems and roughly constant funding. It also means that increased capacity does not hinge on the success of a single concept. In fact, these projects should be monitored closely. If, during concept evaluation, their value becomes questionable, they can be canceled or refocused with a minimal waste of resources. As the program goes on, new concepts for reducing wake vortex constraints may arise and can be rolled into the project schedule at the appropriate time.

Modeling and sensor development will generate important knowledge and the capabilities needed to implement the various capacity enhancers and provide inputs for the systems studies. A constant level of effort should be maintained, addressing needs relevant to each of the time frames. This enabling research provides the seed corn for future concepts and is a basis of the nation's wake turbulence core competence.

The results of this program will be continuous reductions in required wake turbulence spacing. No single answer will totally eliminate the threat of wake vortices, certainly not by 2025. Most solutions will be appropriate for a certain kind of airport or certain weather conditions. However, as more and more capabilities are added, they will build on one another. Table 4-1 shows some of the deliverables distilled from the milestones of this program plan and when they are expected.

TABLE 4-1 Deliverables

Short Term	Medium Term	Long Term
Conservative hazard boundary Outreach efforts to aviation community Wake turbulence encounter reporting system System-level simulations of arrival/departure with operational scenarios, weather scenarios, fleet mixes, and airport layouts Weather data needs coordinated with WRF effort Probabilistic wake vortex model	Fleetwide simulation capabilities for gate-to-gate operations All-weather wake vortex measurement system Airborne wake vortex sensor Wake vortex measurement network Conditional spacing reduction to CSPA at selected airports	Refined and tested hazard boundary Pilot training for wake vortex System-level simulations with effects of uncertainty High-resolution, all-weather wake vortex measurement system High-resolution, all-weather wake vortex measurement network Conditional spacing reduction to CSPA at all airports Conditional spacing reduction for single runway approaches at selected airports Visualization systems[a] Alleviation methods and devices[a] Dynamic spacing[a]

NOTE: WRF, Weather Research and Forecasting; CSPA, closely spaced parallel approach.

[a] Research would be completed in the long term, but deliverable would not yet be available.

Recommendation 4-1. Wake turbulence research should pursue multiple tracks, with the goal of a robust, stable program that will provide continuing reductions in aircraft spacing as new ideas and technologies are developed and proven.

PERIODIC ASSESSMENT

The program recommended in this chapter is a living one. Based on current knowledge, the challenges outlined in this report are believed to afford the best potential for achieving the goals of NextGen. However, in the next few years, the air transportation system will undergo many changes, some of which could invalidate some of these concepts and inspire new ones. Wake turbulence research should be constantly kept relevant throughout the evolution of the NextGen system. In fact, as the

TABLE 4-2 Evaluation Metrics

	Metrics
Supporting studies	Number of parameters included in analysis Amount of data collected Variety of data collected Computational efficiency of models Applicability to flight simulators for pilot training
Enabling research	Temporal and spatial resolution Low uncertainty Weather tolerance Accuracy in the characterization of —Lateral wake location —Vertical wake location —Wake strength —Meteorological conditions Speed —Computational efficiency —Time response of measurement systems
Capacity enhancers	Capacity provided Delays reduced Cost Precision Accuracy Predictability (Will you know how much capacity you have?) Robust to —Airports —Aircraft —Weather conditions —Traffic conditions

program plan shows, research need not grind to a halt when NextGen is implemented. More capacity may be needed in the future; in addition, these technologies may provide other benefits such as safety, efficiency, and situational awareness.

There are two ways to measure progress in addressing a challenge. The first is to view its progression along a planned path. This can be done using the milestones listed for each challenge in Chapter 3 and the deliverables shown in Table 4-1. The second involves evaluation against a metric, which allows comparing alternative projects. The metrics for the three categories of challenge are listed in Table 4-2.

Recommendation 4-2: Wake vortex research priorities should be periodically reexamined.

ROLES

In Chapter 2, the committee discusses the roles of various federal agencies and recommends that the FAA take leadership and oversight of wake turbulence research as a whole; that NASA assist in aeronautics and airspace systems research; that the JPDO assist in identifying research needs and providing system-level studies, and that the WRF modeling group expand its weather prediction system to include parameters needed for wake vortex characterization and implementation of dynamic spacing.

In the past, federal wake turbulence research has taken advantage of outside resources. The Volpe Transportation Research Center has collected a great deal of the existing empirical data. MITRE Corporation's Center for Advanced Aviation System Development has performed systems modeling and human-in-the-loop testing. MIT's Lincoln Laboratory has researched localized weather prediction and built operational prototypes of FAA systems. Companies like Boeing, Lockheed Martin, and Northwest Research Associates and universities like George Mason University, the University of California at Berkeley, and the Naval Postgraduate School have also been involved.

Recommendation 4-3: The federal wake turbulence R&D enterprise should continue its relationships with a balanced mix of government laboratories, industry, and academia.

5

Findings and Recommendations

A complete list of the committee's findings and recommendations appears below, in the order in which they appear in the report.

Finding 1-1. Air transportation system capacity could be significantly enhanced by applying the results of robust and focused wake vortex research and development. These results will be required in order to use the system at its maximum efficiency.

Recommendation 1-1. Aircraft wake vortex characteristics of transport airplanes operating in the national airspace system should be assessed using the best standardized techniques prior to their introduction into service, so that appropriate separation criteria may be established with regard to each new aircraft model. The details of this assessment should vary based on the impact any new aircraft is expected to have on the system, with large and heavy aircraft receiving more emphasis than small ones in terms of data requirements.

Finding 2-1. There is no champion, spokesperson, or leader held accountable for goal achievement across the nation's wake turbulence research and development efforts.

Finding 2-2. Wake turbulence is a long-term problem. Although a total solution cannot be achieved within a decade, improvements will become available gradually, depending on funding, and it can be envi-

sioned that these incremental improvements will provide incrementally increased capacity at airports where implemented.

Recommendation 2-1. Federal wake turbulence research should have the following characteristics:

- **The FAA should be the lead agency for defining requirements for wake turbulence research.**
- **The FAA should manage and fund capacity-focused wake turbulence research using academic, industry, and other government partners.**
- **The FAA should appoint a strong and motivated leader to integrate and coordinate research across agencies, define priorities, and represent wake vortex research to the JPDO and other agencies.**
- **Research should be sustained over the short, medium, and long term.**
- **Resource allocations across functional lines of involved agencies should be coordinated among all agencies involved in this work.**

Finding 2-3. The change in aeronautics research priorities at NASA has led to a gap in the wake turbulence program as previously envisioned.

Finding 2-4. Present federal investment does not place sufficient priority on wake turbulence research to achieve the results called for by the NextGen goals.

Finding 2-5. NASA expertise is well-aligned to conducting medium- to long-term fundamental research, including wake vortex modeling and wake vortex alleviation work, while the FAA does not currently have such expertise.

Recommendation 2-2. Because of its expertise, NASA should continue to conduct medium- to long-term fundamental research, including wake vortex modeling and wake vortex alleviation work at a level of effort sufficient to achieve NextGen goals.

Recommendation 2-3. Operators and controllers should be included in the process of designing, implementing, and evaluating wake turbulence-related changes to the air transportation system.

Recommendation 2-4. JPDO should recommend to the FAA detailed wake vortex research efforts needed to support NextGen.

Finding 3-1. En route wake vortex issues may arise, especially for very light jets in cruise.

Recommendation 3-1. The JPDO should investigate and define specific requirements for research on the impact of cruise-altitude-generated wakes on capacity (including climb and descent) to avoid future problems as fleet diversity increases.

Finding 3-2. NextGen is expected to include separation management capable of permitting reduced and dynamic separation standards.

Recommendation 3-2. JPDO should conduct a detailed analysis of what wake turbulence research and development is needed to achieve its separation management capability goals, and provide a detailed plan with milestones that will lead to successful development in the required time frame.

Finding 3-3. Reducing the spacing needed to avoid wake turbulence will allow more efficient usage of existing runways.

Recommendation 3-3. The FAA, assisted by NASA, should continue its current improved spacing programs, which promise results in the short and medium terms.

Finding 3-4. In many airports, the use of dynamic wake vortex spacing standards could permit parallel runways to be built closer together, meaning that in some cases, new runways may be built between existing runways, or elsewhere on existing airport property.

Recommendation 3-4. The FAA should pursue work in the short and medium terms to determine minimum runway spacing for future airport expansion, which is needed to achieve capacity goals in the long term.

Finding 3-5. Onboard wake vortex visualization has been demonstrated in a proof-of-concept trial and can provide a safety net for dynamic spacing procedures.

Recommendation 3-5. Wake vortex visualization concepts should be further explored and pursued.

Finding 3-6. Vortex alleviation has the potential to significantly impact aircraft spacing requirements in the long term.

Recommendation 3-6. Vortex alleviation ideas, including configuration changes and active and passive forcing, should be explored.

Finding 3-7. NASA's aeronautics program is well-aligned to conduct wake vortex alleviation work as medium- to long-term foundational research.

Finding 3-8. The Weather Research and Forecasting model currently in development can provide the necessary weather prediction resolution to support the needs of NextGen. However, as presently conceived the model lacks the ability to incorporate eddy dissipation rates and thus will not provide the optimal set of parameters for predicting wake turbulence.

Recommendation 3-7. Federal wake turbulence research should engage the Weather Research and Forecasting model effort in order to identify the optimal set of weather parameters needed for predicting wake turbulence.

Finding 3-9. European forecast models have demonstrated some short-term terminal area wake vortex forecast capability.

Recommendation 3-8. Research should be done to ensure that weather modeling is adequate to predict wake vortex movement and decay.

Finding 3-10. Wake vortex modeling is an essential element for most concepts aimed at reducing IFR spacing requirements.

Finding 3-11. NASA's aeronautics program is well-aligned to conduct medium- to long-term foundational wake vortex modeling.

Finding 3-12. Research and development of high-resolution wake vortex measurement sensors to support wake vortex modeling efforts has stalled since the late 1990s.

Finding 3-13. No high-resolution wake vortex measurement system capable of operating in inclement weather exists.

Recommendation 3-9. Explore concepts for an all-weather, aircraft-based wake vortex measurement system that provides information on the location of the wake.

Recommendation 3-10. Develop an all-weather wake vortex measurement system that provides high-resolution measurements of wake vortex characteristics sufficient to validate wake vortex modeling.

Finding 3-14. Although the current air transportation system was designed to avoid wake vortex encounters, they do occur and are safely tolerated using present spacing criteria.

Finding 3-15. It is difficult to quantify acceptable reductions in wake turbulence spacing because there is no agreed metric for, nor definition of, hazard boundaries for wake encounters.

Recommendation 3-11. A hazard boundary needs to be defined and used as a metric in forming spacing criteria.

Finding 3-16. Implementing a system to gather data on wake events in the short term could establish a baseline that could be used to quantitatively evaluate potential solutions, as well as gain the support from the operator and ATC community that will be necessary to increase system capacity.

Finding 3-17. System-level studies are an essential element of a wake turbulence research program. They are basic to ensuring that (1) research priorities will be set in a rational manner, (2) the actual realizable benefits of wake turbulence solutions will be known, (3) key constraints can be identified, and (4) NextGen capacity goals can be achieved.

Recommendation 3-12. The current JPDO research in system-level modeling of the air transportation system should be continued and resources should be directed to extending simulation capabilities to cover a range of operational scenarios, weather scenarios, fleet mixes, and airport layouts.

Recommendation 4-1. Wake turbulence research should pursue multiple tracks, with the goal of a robust, stable program that will provide continuing reductions in aircraft spacing as new ideas and technologies are developed and proven.

Recommendation 4-2. Wake vortex research priorities should be periodically reexamined.

Recommendation 4-3. The federal wake turbulence R&D enterprise should continue its relationships with a balanced mix of government laboratories, industry, and academia.

Appendixes

A

Statement of Task

The National Research Council will assemble a committee to conduct an independent analysis of what should be the appropriate elements of a national approach to overcoming wake turbulence challenges. The analysis will include the following:

Step 1: An analysis to identify what are the most important challenges to address, and why. These challenges should be prioritized, and strong consideration should be given to the impact of the ability to solve these challenges on the successful realization of the NGATS. A recommendation will be made as to which federal agency, or agencies, including NASA, the FAA, NOAA, or other, should lead the research effort for each of the identified challenges. The committee will then develop a draft program plan that addresses these challenges. This plan will include milestones, metrics, and a schedule.

Step 2: An assessment of the current relevant research being conducted by NASA, the FAA, and other federal government agencies. The existing and/or potential gaps between the recommended program from Step 1 and the current research activities will be identified. Recommendations will be made regarding how best to address these identified gaps.

Step 3: A review of research being conducted by nonfederal government organizations within the United States and by foreign organizations in the area of wake turbulence. Of interest is the extent to which this non-U.S.-federal government research is being sufficiently leveraged by the existing national research program(s). This will include proposing changes in roles and responsibilities required in existing partnerships including FAA/Eurocontrol Action Plan 14 and WakeNet USA, as applicable.

B

Committee Biographies

ANTHONY J. BRODERICK, *Chair*, is an independent aviation safety consultant who works with international airlines, aerospace firms, a major aircraft manufacturer, and governments. Before retiring from his post as associate administrator for regulation and certification in the FAA, Mr. Broderick served for 11 years as the senior career aviation safety official in the U.S. government. He led the FAA's development of the International Aviation Safety Assessment program and was also instrumental in leading international efforts to establish certification and operational standards for safety. Prior to this appointment, Mr. Broderick spent 14 years at the FAA and the U.S. Department of Transportation (DOT), and 7 years in private industry. His portfolio also includes a background in civil aviation security; aviation environmental issues; management of the FAA evaluation, currency, and transportation flying programs; and oversight of the FAA flight inspection program. Mr. Broderick is a private pilot. He has received many awards and recognition for his work in the aeronautics industry and is a fellow of the Royal Aeronautical Society. He is a member of the Aeronautics and Space Engineering Board and has served on two other NRC studies—as a member of the Panel on Transportation for Science and Technology for Countering Terrorism and of the Committee on Aeronautics Research and Technology for Environmental Compatibility.

PAUL BEVILAQUA is manager of advanced programs at the Lockheed Martin Aeronautics Company. He joined Lockheed Martin as chief aeronautical scientist of the Lockheed Advanced Aeronautics Company and became chief engineer of advanced development projects in the Lockheed Martin Skunk Works. During that time he played a leading role in creating the Joint Strike Fighter program and invented the lift fan propulsion system that makes it possible to build variants of a single stealthy, supersonic V/STOL aircraft for the Air Force, Marines, and Navy. Prior to joining Lockheed Martin, he managed advanced programs at Rockwell International's Navy aircraft plant. He began his career as a captain in the U.S. Air Force and deputy director of the Energy Conversion Laboratory at Wright Patterson Air Force Base. Dr. Bevilaqua has a B.S. from the University of Notre Dame and graduate engineering degrees from Purdue University. He is a member of the NAE and a fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is the recipient of an Air Force Scientific Achievement Award for his contributions to turbulence theory, the AIAA Newbold Award for his contributions to V/STOL aircraft technology, the AIAA and Society of Automotive Engineers (SAE) aircraft design awards for his contributions to aircraft design, and the Collier Trophy for his lift fan propulsion system. His publications include articles in the journals of the AIAA, the journals of the Royal Aeronautical Society, and the proceedings of many meetings and symposia. He has served on three other NRC committees: the Committee on Sea Basing: Ensuring Joint Force Access from the Sea, the Panel on Aerodynamics and Aeroacoustics of the Decadal Survey of Civil Aeronautics, and the Panel on Air and Ground Vehicle Technology.

JEFFREY CROUCH is a senior technical fellow in the enabling technology and research organization at Boeing Commercial Airplanes. Dr. Crouch received his Ph.D. in engineering mechanics from Virginia Tech. Prior to joining the Boeing Company in 1992, he was an ONT postdoctoral fellow at the Naval Research Laboratory. His responsibilities at Boeing include research, consultation, and technology development. His research has considered topics in hydrodynamic stability, boundary-layer transition prediction, laminar-flow control, transonic-buffet prediction, wake-vortex instabilities, and modeling and control of wake vortices. Dr. Crouch's research on wake vortices led to the discovery of new instabilities and new concepts for wake vortex alleviation. He has published over 50 papers and recently was co-editor of a special issue of the French Academy of Sciences journal *Comptes Rendus Physique* entitled "Airplane Trailing Vortices."

FREDERICK GREGORY is the managing director of aerospace and defense strategies at Lohfeld Consulting Group. He retired as the deputy administrator of NASA in 2005. Management positions at NASA included acting administrator, associate administrator for spaceflight, and associate administrator, Office of Safety and Mission Assurance. He was selected as an astronaut in January 1978 and has logged 455 hours in space. He graduated from the U.S. Naval Test Pilot School and served as an engineering test pilot for the Air Force and for NASA, retiring from the Air Force as a colonel in 1993. He has authored or co-authored several papers in the areas of aircraft handling qualities and cockpit design. Mr. Gregory holds a B.S. from the U.S. Air Force Academy and a master's degree in information systems from George Washington University. He is a member or past member of numerous societies, including the Society of Experimental Test Pilots, American Helicopter Society, AIAA, and the Tuskegee Airmen. Mr. Gregory has received numerous awards from the military and NASA, as well as honorary doctorates from the College of Aeronautics, the University of the District of Columbia, and Southeastern University. In 2004 and 2005, he was designated one of the "50 Most Important Blacks in Technology." He holds an FAA commercial and instrument certificate for single- and multiengine airplanes and helicopters, having logged 7,000 hours.

FAZLE HUSSAIN is the Cullen Distinguished Professor at the University of Houston (UH) and director of the Institute for Fluid Dynamics and Turbulence. After his Ph.D. at Stanford and postdoctoral research at Johns Hopkins, he joined UH in 1971. His primary research interest is turbulent flows and vortex dynamics, with an emphasis on coherent structures. He has authored over 220 technical papers and has presented numerous keynote and invited lectures at major conferences. He has served as associate editor on the *Journal of Fluids Engineering* and *Physics of Fluids*. Dr. Hussain has received four of the most coveted awards in fluid dynamics: the Freeman Scholar Award from the American Society of Mechanical Engineers (ASME), the Fluid Dynamics Prize from the American Physical Society (APS), the Fluids Engineering Award from the ASME, and the Fluid Dynamics Award from the AIAA. He is a fellow of the AIAA, APS, and ASME, and he served as chair of the Fluid Dynamics Division of APS. He is a member of the NAE and an officer in the NAE Mechanical Engineering Section and has served on one other NRC study—the Committee for Naval Hydromechanics Science and Technology—in addition to numerous other advisory panels.

BILL F. JEFFERS recently retired as senior director of FAA programs at ARINC, Inc. Prior to that, he spent over 30 years at the FAA, in positions from air traffic controller through senior management. In his most recent position, associate administrator for air traffic, he provided executive direction for all organizations in the Air Traffic Service, including directing, coordinating, controlling, and ensuring the safe and efficient use of the National Airspace System. He attended Athens State College, Montevallo University, and the Kellogg School of Northwestern University. Mr. Jeffers is a member of the Air Traffic Control Association and the National Business Aviation Association (NBAA). He is a former chair of the Program Management Committee of the Radio Technical Commission for Aeronautics (RTCA), a former member of the RTCA Free Flight Steering Committee, and a current member of the Air Traffic Management Advisory Committee's (ATMAC's) Requirements and Planning Working Group and the NBAA Airspace and Air Traffic Committee.

DENNIS W. NEWTON is an independent consultant and designated engineering representative flight test pilot for both small and transport airplanes. He currently serves on the SAE AC-9C Icing Subcommittee and the Society of Experimental Test Pilots' Flight Test Safety Committee. He has a B.S. in engineering science and an M.S. in meteorology from the Pennsylvania State University. Throughout his career he has worked as a test and research pilot for the Boeing Company, the FAA, LearFan Ltd., Cessna, and the meteorology department of Pennsylvania State University. Mr. Newton wrote the textbook *Severe Weather Flying*, as well as numerous technical papers and magazine articles. He is a fellow of the Royal Aeronautical Society, an associate fellow of the AIAA, and a member of the Society of Experimental Test Pilots. In 2005, he was awarded the Losey Atmospheric Sciences Award from the AIAA. Mr. Newton holds Airline Transport Pilot type ratings in six jet and three turboprop airplanes and is instructor-rated in single- and multiengine airplanes and gliders.

DUNG PHU "CHI" NGUYEN is a director of aerospace engineering with more than 17 years of industry experience in aeronautical and space systems. As an employee of Research Triangle Institute (RTI), Dr. Nguyen has made significant contributions to NASA's Aviation Safety Program, including Enhanced Vision Systems, and to the Aircraft Vortex Spacing System (AVOSS) and has developed a unique RTI capability in data processing for radar, lidar, and electro-optical sensor systems. He has provided expertise on selected NASA Engineering Safety Center teams for independent assessment of space shuttle and International Space Station anomalies. Dr. Nguyen has worked with and is familiar with many aircraft surveillance (active and passive) technologies and airport reporting databases. He has extensive field testing and flight testing experience. In addition to his engineering skills, Dr. Nguyen has extensive operational experience with software systems. He has published numerous technical reports and has coauthored conference papers on wake vortex lidar, sensor systems, and space exploration concepts. Dr. Nguyen is also an active associate professor at the George Washington University School of Engineering and Applied Science. He teaches graduate engineering courses in operational research, statistics, decision analysis, and technology management.

J. DAVID POWELL is an emeritus professor in the Aeronautics and Astronautics Department at Stanford University, from which he received M.S. and Ph.D. degrees in 1966 and 1970, respectively. He received a B.S. in mechanical engineering from the Massachusetts Institute of Technology (MIT) in 1960. Dr. Powell has been on the Stanford faculty since 1971. He continues to be active in research since becoming emeritus in 1998. His research interests included space tether dynamics and control, internal combustion engine control, and the design of aerospace digital flight control systems. More recently, his research focus has been GPS-based attitude determination augmented with inertial sensors, the use of GPS for air and land vehicle surveillance and navigation, and the design of GPS-aided flight displays that include the depiction of wake vortices. He is the author of more than 100 research papers and two of the leading control textbooks. Dr. Powell is a fellow of AIAA and ASME and is an aircraft owner and instrument-rated pilot. He has served on other NRC committees, including the Panel on Airspace Systems for the Review of NASA's Revolutionize Aviation Program.

ALFRED T. SPAIN retired as senior vice president of operations at JetBlue Airways Corporation in May 2006. Previously, he served in various capacities at Continental Airlines, including as vice president of flight operations for Continental Micronesia, Inc. Prior to that, he was a pilot and instructor for over 20 years. Mr. Spain has a B.S. in professional aviation from Louisiana Technical University and an MBA from Concordia University. He is a senior member of the AIAA, a life member of the Navy League of the United States, and a member of the Aircraft Owners and Pilots Association and the Seaplane Pilots Association. He has experience in the senior management of flight operations for domestic and international airlines as well as civilian and military experience in safety applications for both flight and ground operations. Mr. Spain is pilot-rated in numerous multiengine and turbine-powered aircraft.

ROBERT P. "ROCKY" STONE is the chief technical pilot for United Airlines. He currently flies as a Boeing 737 captain, and he has previous experience as an experimental test pilot in the U.S. Air Force. He earned his B.S. in aerospace engineering from MIT and an M.S. in systems management from the University of Southern California. Mr. Stone is the co-chair of RTCA SC-186, responsible for writing technical standards for ADS-B. He also chairs the meteorology subgroup of RTCA SC-206 on AIS/FIS Data Link.

KAREN WILLCOX is associate professor of aeronautics and astronautics in the Aerospace Computational Design Laboratory at MIT. She received a B.Eng. from the University of Auckland in 1994 and M.S. and Ph.D. degrees in aeronautics and astronautics from MIT in 1996 and 2000, respectively. She spent 1 year as a visiting researcher at Boeing Phantom Works in Long Beach, working with the blended-wing-body design team. She joined the faculty of the Department of Aeronautics and Astronautics in the fall of 2001. Dr. Willcox's research interests lie in the computational simulation and optimization of engineering systems. Her research focuses first on model reduction for large-scale systems, with applications in active flow control, aeroelasticity, and variable-fidelity design methods, and second in multidisciplinary system design and optimization, with particular emphasis on economic and environmental factors in aircraft conceptual design. She served on the NRC Panel on Aerodynamics and Aeroacoustics for the Decadal Survey of Civil Aeronautics.

C

List of Speakers

The National Research Council appreciates the efforts of the individuals who volunteered their time to speak at the meetings of the Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development, as well as the information they provided.

Mark Andrews, Joint Planning and Development Office/Weather Integrated Product Team
Sherry Borener, Joint Planning and Development Office
Dave Clark, Massachusetts Institute of Technology Lincoln Laboratory
William Cotton, Flight Safety Technologies
Bill DeGroh, Air Line Pilots Association
Don Delisi, Northwest Research Associates
Peter Erikson, Eurocontrol
Thomas Gerz, Deutsches Zentrum für Luft- und Raumfahrt
George Greene, Federal Aviation Administration (retired)
James Hallock, Volpe Center for Transportation Research
R. John Hansman, Massachusetts Institute of Technology
David Hinton, NASA Langley Research Center
Debbie Kirkman, Joint Planning and Development Office/Agile Airspace Integrated Product Team
Joydip Kundu, Office of Management and Budget
Dennis Lamy, National Air Traffic Controllers Association
Steven Lang, Federal Aviation Administration
Clark Lunsford, MITRE Corporation

Richard Obermann, House Science and Technology Committee, Space and Aeronautics Subcommittee Staff
Fred Proctor, NASA Langley Research Center
Robie Samanta Roy, Office of Science and Technology Policy
Jeffrey Swingler, Sondei Group
Karlin Roth Toner, NASA Headquarters
Frank Wang, Volpe Center for Transportation Research
Mark Weber, Massachusetts Institute of Technology Lincoln Laboratory

D

Acronyms and Abbreviations

ACES	Airspace Concept Evaluation System
ADS-B	Automatic Dependent Surveillance-Broadcast
ASRS	Aviation Safety Reporting System
ATC	air traffic control
AVOSS	Aircraft Vortex Spacing System
CFD	computational fluid dynamics
CSPA	closely spaced parallel approach
CSPR	closely spaced parallel runway
DFW	Dallas/Fort Worth International Airport
DHS	Department of Homeland Security
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOD	Department of Defense
DOT	Department of Transportation
EDDF	Frankfurt International Airport
EDR	eddy dissipation rate
FAA	Federal Aviation Administration
GPS	Global Positioning System

IAH	George Bush Intercontinental Airport (in Houston)
IFR	Instrument Flight Rule
IMC	instrument meteorological conditions
JFK	John F. Kennedy International Airport
JPDO	Joint Planning and Development Office
LAAS	Local Area Augmentation System
LaRC	Langley Research Center (NASA)
LES	large eddy simulation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NextGen	Next Generation Air Transportation System
NM	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
R&D	research and development
REDAC	Research, Engineering and Development Advisory Committee
RVSM	reduced vertical separation minimum
SFO	San Francisco International Airport
SSWG	Separation Standards Working Group (of the FFA's REDAC)
STL	Lambert-St. Louis International Airport
VESA	Vortex Encounter Severity Assessment
VFR	Visual Flight Rule
VMC	visual meteorological conditions
WAAS	Wide Area Augmentation System
WRF	Weather Research and Forecasting

E

Sample Wake Encounter Reporting Form

The following is a sample wake turbulence encounter reporting form used by the UK Civil Aviation Authority. This format could provide a model for a U.S. reporting form.

UK Civil Aviation Authority

NATS

Civil Aviation Authority

WAKE TURBULENCE ENCOUNTER REPORT FORM - AIR TRAFFIC CONTROL (SRG 1422)

Please complete all relevant sections in BLOCK CAPITALS using black or dark blue ink and put an X in the appropriate boxes.

If report is CONFIDENTIAL, please mark clearly and submit as per CAP 382 paragraph 7.1.8.

For ATCO use when filing a report on wake turbulence encounters, including those hazardous cases that qualify as Reportable Occurrences under Article 142 of the Air Navigation Order and EU Directive 2003/42.

Pilots of both leading and following aircraft involved in a wake turbulence encounter should be requested to complete form SRG 1423, which is available from the CAA website.

1. IS THIS INCIDENT REPORTABLE UNDER THE MOR SCHEME?

Yes ☐ No ☐

If YES, this form should be sent to the Safety Investigation and Data Department (SIDD) (Full address is given at the end of this form).

2. GENERAL DETAILS

Date of incident: .... Time (UTC): ....

Controller name: .... Watch (if applicable): ....

Unit address: ....

....

Telephone: .... E-mail: ....

3. DETAILS OF AFFECTED AIRCRAFT

report:

Operator: .... Callsign: ....

ICAO aircraft type: .... SSR: ....

Geographical position: .... Flight phase: .... Altitude: ....

Departure airport: .... Destination airport: ....

4. DETAILS OF GENERATING AIRCRAFT

Operator: .... Callsign: ....

SSR: .... ICAO aircraft type: ....

Estimated separation between aircraft: ....

5. METEOROLOGY

Wind direction: .... Wind speed: ....

Visibility: .... Cloud: ....

Temperature: .... Dew point: .... QNH: ....

Wind shear known or reported: ....

Weather: ....

6. OTHER INFORMATION

Please enter any further information which you may feel is relevant to this

....

....

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