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Introduction

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These are tumultuous times in the aviation industry, as stakeholders struggle to respond to uncertain fuel prices and availability, a global economic and financial crisis, and increased scrutiny of the environmental impacts of aviation. The potential impacts of aviation on climate—and impacts of climate on aviation—are of particular concern and urgency.

Efforts to minimize environmental impacts increasingly dominate aircraft design and the design, construction, and operation of airports. While environmental issues have become a fundamental constraint to increasing aviation system capacity, constrained capacity can exacerbate certain environmental problems, such as noise and impacts on local air quality.

Some environmental impacts are well understood, while significant research will be required to understand other existing and future ones, as well as the opportunities for mitigating or avoiding them. For example, better science-based understanding of the impacts of aviation emissions on climate change is needed to formulate an appropriate response. In addition, improved metrics, measurement techniques, and modeling capabilities are needed to quantify and predict impacts and their consequences, and to understand interrelationships of aviation-related environmental issues. This circular summarizes the progress being made and suggests additional research to help achieve that vision.

OVERVIEW

The Transportation Research Board (TRB) Environmental Impacts of Aviation Committee (AV030) issued its first report on critical issues in aviation and the environment in the United States in 2004 (*1*), followed by revised editions in 2005 (*2*) and 2009 (*3*). This revision updates and expands upon the previous circulars while maintaining their cross-disciplinary approach to reviewing subjects of interest to the civil aviation community in this country. It consists of nine individually authored sections representing the author's expert opinions on issues that address the major environmental media affected by aviation activities and the key processes that link aviation and the environment. As before, the focus is on the state of science, rather than on policy, and on identifying priority research with the potential to yield benefits during the next several years to several decades. Each section is divided into subsections that

- Define the critical issues in the subject area;
- Discuss the current state of practice, research, and policy;
- Define a vision of future capabilities that would address the critical issues; and
- Identify specific research needs to help achieve the vision.

This circular focuses on research conducted in the United States, although international activities are discussed where public or private entities in this country are closely involved. A wide range of published and unpublished material, public information, and individual contributions were collected to prepare these papers, as noted in the references at the end of each section. Because of constraints on time and effort, the portions of each section devoted to critical issues do not necessarily address all potentially critical issues in a given field. For example, this circular does not fully address land use development near airports, which represents a major constraint on future aviation activity and for which effective controls remain to be developed. Threatened and endangered species, air and drinking water quality inside aircraft and airports, and other topics are not addressed but might be added in future revisions. The critical issues listed here have varied and evolved over time and will continue to do so. For example, while aircraft noise impacts once were preeminent among the operational environmental issues associated with aviation, air quality now receives considerable attention at the local, national, and international levels. Water quality issues seem likely to assume the same sort of importance that special status species and wetlands impacts have long held.

The portion of each individually authored section labeled "current state" addresses efforts to advance the resolution of the issues now underway in the broad community of professionals concerned with aviation and the environment. To this end, TRB maintains committees and task forces that focus on specific environmental topics, such as noise and air quality, as well as committees concerned with various aspects of aviation. The Environmental Impacts of Aviation Committee coordinates with these committees in planning meetings, annual meeting sessions, paper reviews, and related matters. The current state portions of this circular help to further a goal of the Environmental Impacts of Aviation Committee: to integrate the work of other TRB committees, along with research produced in the various sectors of the aviation community, into a summary document focused on research addressing the environmental impacts of aviation.

CURRENT STATE

In 2003, Congress chartered the Joint Planning and Development Office, tasked with designing and implementing the Next Generation Air Transportation System (NextGen) to accommodate future growth in the national airspace system. NextGen's environmental goals are to achieve absolute reductions in significant impacts on community noise levels and local air quality, limit or reduce the impacts of aviation greenhouse gas (GHG) emissions on the global climate, reduce significant impacts on water quality, improve energy efficiency throughout the national airspace system, and support the development of alternative fuels for aviation.

In support of these goals, the Federal Aviation Administration (FAA) established the Continuous Lower Energy, Emissions, and Noise engine and airframe technology program, charged with developing technology to increase fuel efficiency by 33%, reduce landing and take-off emissions of nitrogen oxide by 60%, and reduce noise levels 32 decibels (dB) below the current international standard. In 2010, the agency awarded its first contracts to develop and demonstrate new technologies aimed at reducing jet fuel consumption, emissions, and noise.

Also in 2003, Congress authorized the Airport Cooperative Research Program (ACRP) and FAA launched Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), an FAA Center of Excellence cosponsored by the National Aeronautics and Space Administration and Transport Canada. Headquartered at the Massachusetts Institute of Technology, PARTNER's mission is to foster breakthrough technological, operational, policy, and workforce advances for the betterment of mobility, economy, national security, and the environment. To date, it has sponsored more than 36 research projects in the areas of alternative fuels, emissions, noise, operations, tools, and system-level/policy assessment, including a 2004 report to Congress that proposed a national vision statement and recommended actions regarding aviation and environment.

Under a contract between FAA and the National Academies, TRB manages ACRP to select and fund research projects identified by airports as having high priority, clearly defined objectives, and immediate practical applications. In less than 5 years of operation, the ACRP has funded or approved more than 40 research projects directly related to environment, including investigations into GHG emissions, hazardous air pollutants, particulate emissions, community responses to aircraft noise, alternative deicing and anti-icing formulations, alternative fuels, and a comprehensive development plan for a multimodal noise and emissions model.

The portions of this document labeled "research needs" draw on recommendations detailed in the National Research Council report that led to the establishment of ACRP, as well as additional needs subsequently identified by the section authors. Research needs identified in this circular could, in turn, suggest projects that can be realized through PARTNER and ACRP.

ACKNOWLEDGMENTS

This circular contains nine individually authored sections that represent the viewpoints of the attributed authors. Members and friends of the Environmental Impacts of Aviation Committee also reviewed and contributed comments to these sections. Specific acknowledgment is extended to the following contributors for their helpful assistance during the committee review process:

- Lourdes Maurice, Federal Aviation Administration, Office of Environment and Energy and
- David O. Bell, *Aviation and Environment News;* Lead Editor of this document.

The TRB Environmental Impacts of Aviation Committee welcomes comments on this document. Please address them to the Committee Chair.

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Noise

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Historically, aircraft noise has been a major constraint to increasing civil aviation capacity. Despite the facts that community exposure to aircraft noise has decreased markedly over the past several decades (Figure 1) and that the United States and the European Union have ambitious technology goals for the future, community expectations of continued decreases in noise levels may not reflect the reality of the extended time frame required for development and adoption of advanced technology for the next generation of quieter aircraft.

CURRENT STATE

The state of the practice for aviation noise assessment has been constant for more than thirty years, and relies on a noise and land use compatibility guideline of Day-Night Average Sound Level (DNL) of 65 decibels. DNL 65 was first identified by researchers in the 1970s, and was adopted as follows:

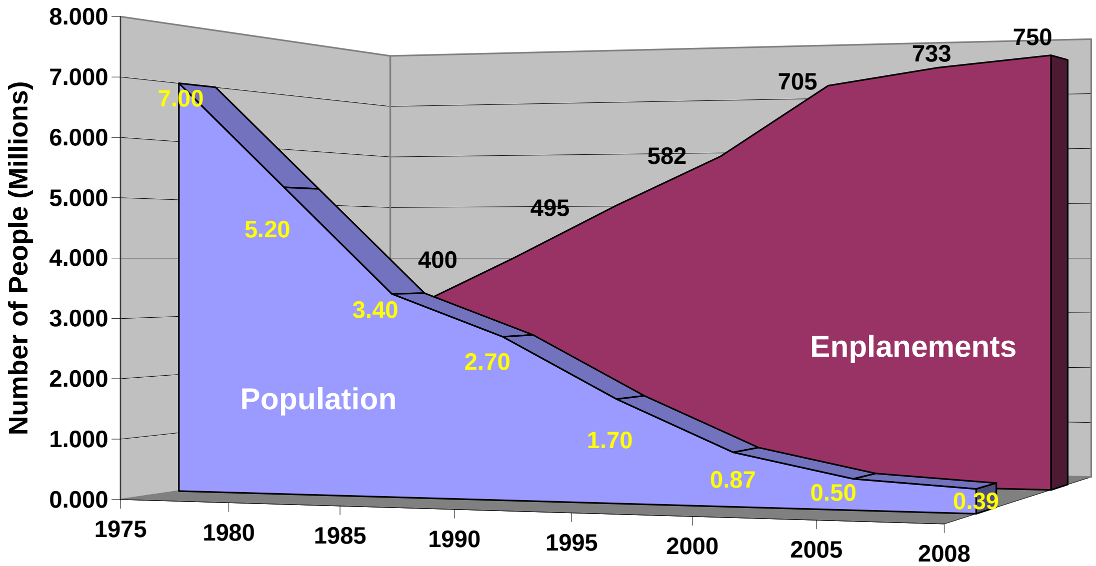

FIGURE 1 Noise exposure versus enplanements. (Source: FAA, 2010.)

- In 1970, the State of California identified an airport noise criterion of Community Noise Equivalent Level[1] (CNEL) 65, based largely on community reaction, but also in light of a review of considerable research on the effects of noise on people. Of note is the clear recommendation in an accompanying report that: "The CNEL limit should be periodically reviewed by the State with a view to the possible necessity of reducing the limit in light of any new human factors research which may become available," and that the review should be every 5 years, at maximum.[2]
- In 1971, the Department of Housing and Urban Development developed its own land use compatibility guidelines, with much of the analysis grounded in social surveys conducted by Ted Schultz. Schultz identified Noise Exposure Forecast (NEF) 30"[3] as the criterion of acceptable exposure in the U.S. This criterion appears to be a synthesis of what other countries were doing.[4]
- The U.S. Environmental Protection Agency Task Group III, in responding to the Noise Control Act of 1972, recommended DNL 60 as the limit of compatibility, and based this conclusion on minimizing annoyance, complaints and community reaction, and speech interference both outdoors and indoors.
- In 1975, the Maryland Aviation Administration recommended DNL 65 as the residential standard, to be reduced to DNL 60 when "the U.S. fleet noise level is reduced 5 dB below 1 July 1975 levels."[5]

The technical bases for FAA's noise policies were last reviewed in 1992. Currently, this policy identifies a value of DNL 65 dB as the threshold of significant impact for purposes of the National Environmental Policy Act (NEPA) analyses of FAA major actions. This threshold corresponds to about 13% of the population that will report high annoyance. The policy is to be based on the best available scientific evidence on the "surveyed reactions of individuals" to aircraft noise and should this relationship be outdated, a policy review/update would be appropriate.[6]

Civil aviation noise research in the United States is led by two federal agencies. The Federal Aviation Administration's research mission focuses on aviation effects and near- to mid-term technological improvements, while NASA's research agenda is more focused on fundamental research that will lead toward development of new aviation technology. Both

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[1]CNEL is a 24-hour cumulative metric like DNL, with the exception that noise occurring between 7 and 10 pm is assigned a weighting of three times (4.77 dB).

[2]"Supporting Information for the Adopted Noise Regulations for California Airports," WCR 70-3(R), January 29, 1971.

[3]NEF is Noise Exposure Forecast metric, roughly equivalent to DNL 65.

[4]Of particular interest is the following statement: "It should be emphasized that criteria in the NEF 30 range must be regarded as provisional. In each of the national studies in which these limits were developed, these levels of noise showed up as 'maximum tolerable' and were regarded as turning points above which annoyance increased very rapidly; but sizable portions of the population were seriously disturbed at much lower levels. These turning points, however, were seized by the authorities and treated as acceptable levels such that special precautions and noise abatement measures are required only for *more severe exposure* [Original emphasis]. The situation is even more extreme in the U.S., since the criteria are based on overt action in terms of complaints or legal action. It is well known that serious public annoyance is prevalent long before official complaints are lodged. It is therefore obvious that these criteria are not adequate for aircraft noise abatement in the long run, since they are deliberately permissive."

[5]Maryland Department of Transportation, State Aviation Administration, "Selection of Airport Noise Analysis Method and Exposure Limits," January 1975.

[6]49 U.S.C. § 47502.

agencies are engaged in the development of new research roadmaps for aviation noise. They also collaborate extensively with industry, academia, and other partners to advance national research goals. Several significant programs for advancement of aviation noise research include the Partnership for AiR Transportation Noise and Emissions Reduction, ACRP, and the Continuous Lower Energy, Emissions, and Noise program, all funded through FAA.

United States federal agencies coordinate aviation noise research priorities and findings through the Federal Interagency Committee on Aviation Noise (FICAN). Its members include the following agencies and departments of the U. S. Government: the Department of Transportation, Department of Defense (DOD), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), Department of Housing and Urban Development, and Department of the Interior (DOI). Research also is coordinated through the Joint Planning and Development Office Environmental Working Group, which consists of the FAA, NASA, EPA, DOD, Department of Commerce, Council on Environmental Quality, DOI, and Office of the Secretary of Transportation, as well as industry, academia, local government, and community groups.

FUTURE VISION

Comprehensive aviation noise research would provide the needed scientific basis for examining or updating FAA noise policy and insure decisions about major FAA actions and any FAA-sponsored airport noise studies would be informed by the best available information. Four goals have been identified:

- First, with the proper technical evidence, FAA could update land use compatibility guidelines, NEPA significance thresholds, and criteria for judging and targeting mitigation measures.
- Second, application of up-to-date research results would help build public trust in noise analyses and, through better communication, increase understanding about aircraft noise, its effects, and the likely changes that can be expected from airport and airspace projects.
- Third, updated research results can focus noise abatement, airport, or airspace design efforts for efficiency and help to balance noise with other environmental considerations, where and when it matters.
- Finally, updated research would advance the civil aviation system need to improve capacity and efficiency with minimal adverse noise-related public action.

RESEARCH NEEDS

The FAA has identified four critical research areas: noise effects on health and welfare, noise in National Parks and wilderness, NextGen noise modeling enhancements, and costs of aircraft noise on society. Other members of FICAN concur with these priorities for research. Each of these is described in detail below.

Noise Effects on Health and Welfare

In 2009–2010, the FAA developed a Noise Research Roadmap that has identified the need for research in the following areas:

- Annoyance: In discussing annoyance, it is important to distinguish between private annoyance (how an individual feels, which can only be effectively measured through surveys) and public action (how an individual or group reacts, through complaints, organized opposition, legal action, etc). Several key research questions regarding both public and private annoyance have been posed, including
    - How well does the FICON relationship between annoyance and DNL apply to U.S. airport communities today?
    - Can we develop an annoyance model with greater predictive ability? For example, has annoyance increased with time? Or is it different for different aircraft? Is it location dependent – i.e., does low frequency content affect annoyance? Is annoyance due to a step change in exposure the same as annoyance for more gradual changes?
    - How well does DNL capture nonacoustic factors?
    - What factors affect private annoyance as determined through social surveys?
    - Can community and public actions be predicted?
    - What can be learned from complaint data?
    - Can models or standards for communicating aircraft noise exposure and effects to the public be developed?
- Sleep disturbance: Much research has been conducted on sleep disturbance generally, but there is still no consensus on the best method for studying noise-induced awakenings. Research questions include
    - Can nonnoise sleep disturbance studies of health effects be useful for noise-induced sleep disturbance?
    - Can results from studies performed outside the United States be transferred 1:1 to U.S. populations?
    - Regarding reliability of different sleep disturbance models, is there a noise exposure-response relationship for sleep disturbance we can use?[7]
- Effects of noise on children's learning: Although there has been considerable research conducted on the effects of noise on children's learning, there is currently no standard impact criterion or methodology for airport operators to use to identify potential impacts caused by airport operations and/or proposed airport projects. The FAA has set aside further development of a research plan on learning pending the results of ACRP Project 02-26, *Assessing Aircraft Noise Conditions Affecting Student Learning*.

Some of the above questions on annoyance and sleep disturbance might be answered through ACRP Research Project 02-35, *Understanding Public Perception of Aircraft Noise and Noise-induced Sleep Disturbance.*

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[7] An initial effort at a sleep disturbance model has been developed by Committee S12 of the American National Standards Institute, ANSI S12.9-2008/Part 6 "Methods for Estimation of Awakenings Associated with Outdoor Noise Events Heard in Homes." FICAN has approved this standard for use in estimating behavioral awakenings from aircraft.

Noise in National Parks and Wilderness Areas

There has been significant interest in the issue of aviation noise in national parks for many years, first described in the National Parks Overflights Act of 1987. FAA and National Park Service (NPS) research efforts are focused on two principal areas:

- Visitor response: The current effort is a 2-year research plan that is reevaluating previously collected dose-response data from park visitors and developing pilot studies of new research. At the same time, researchers are developing a long-term study plan.
- Wildlife: FAA and NPS are jointly developing a research plan to address noise impacts to wildlife in national parks. It is likely this research agenda will follow a similar path as the visitor response research program, and an initial plan is expected this year.

NextGen Noise Modeling Enhancements

FAA is currently developing tools to address noise from entire aircraft operations on the ground and in the air, including potential future unconventional aircraft and engine configurations. This effort is discussed in detail in the *Next Generation of Aviation Environmental Modeling Tools Suite* chapter of this document.

Social Costs of Aircraft Noise on Society

FAA is developing tools to monetize the social cost of aircraft noise on society through its Aviation Portfolio Management Tool. The goal of this effort is to develop a common methodology for assessing environmental impacts that will facilitate informed decision-making. This effort also is discussed in detail in the *Next Generation of Aviation Environmental Modeling Tools Suite* chapter of this document.

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Local Air Quality

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Over the past two decades air pollution associated with aviation and airport-related sources has become a prominent issue facing many air carrier and general aviation airports in the United States. Today, aviation emissions are estimated to account for less than 1 percent of concentrations of the criteria pollutants carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) and its precursors, oxides of nitrogen (NO_x) and volatile organic compounds (VOCs), sulfur dioxide (SO_2), and particulate matter (PM_{10} and $PM_{2.5}$) over the United States, according to recent Government Accountability Office testimony (*1*).[1] Nevertheless, aviation sources, like those associated with other transport modes, can contribute to air quality degradation issues and that contribution may grow. Worldwide aviation traffic is expected to increase at an average annual rate of approximately 4.2% per year between 2010 and 2030, taking into account the recession of 2009 (*2*). Increased aviation demand and activities will likely lead to an increase in aviation emissions.

At present, many of the busiest airports in the United States are located in the non-attainment and maintenance areas for National Ambient Air Quality Standards established by the Environmental Protection Agency (EPA). The number of these airports in nonattainment areas is expected to increase as more stringent air quality standards are adopted by EPA, something that has been done frequently in the past 5 years. For example, in 2006, EPA lowered the 24-hour $PM_{2.5}$ standard from 65 micrograms per cubic meter ($\mu g/m^3$) to 35 $\mu g/m^3$ (*3*), with 122 counties designated to be in nonattainment with the new standard. EPA revised the 8-hour ozone standard from an effective value of 84 parts per billion (ppb) down to 75 ppb for both primary and secondary standards in 2008 (*4*). This change potentially increased the number of counties in ozone nonattainment from 85 to more than 300. However, in January 2010 EPA proposed to again lower the primary ozone standard to a level in the range of 60 to 70 ppb (*5*), which would add even more counties to the list of ozone nonattainment areas. Also in 2008, EPA lowered the existing lead standard 10-fold to 0.15 $\mu g/m^3$ for a 3-month rolling average (*6*), which may cause counties with substantial general aviation activity (fueled with leaded aviation gasoline) to be designated as nonattainment for lead. In 2009, EPA proposed to create a new primary 1-hour SO_2 standard to be in the range of 50 to100 ppb (74 FR 64810). Finally, in January 2010, EPA finalized a rule that created a new 1-hour NO_2 primary standard at 100 ppb and expanded the

[1]Note that aircraft usage of leaded aviation gasoline (avgas) is a known contributor to atmospheric lead concentrations; over 50 percent of the 2005 EPA National Emissions Inventory (NEI) for lead is composed of emissions from leaded avgas usage, indicating that the usage of this fuel can be a major contributor to lead in the air (*8*).

NO_2 monitoring network, particularly by creating a monitor network intended to measure NO_2 peaks at roadways (*9*). Increased attention to short-term peak concentrations of NO_x may lead to increased pressure to characterize peak NO_x concentrations in airport vicinities.

Numerous sources (aircraft, stationary sources, ground support equipment, ground access vehicles, and auxiliary power units) contribute to overall emissions originating from airport activities. In general, aircraft are the major contributor to airport emissions. Aircraft emit emissions both at the surface and along the flight path. Aircraft emit the bulk of the emissions (~90 percent) above 3,000 ft of altitude. Traditionally, aircraft emissions within the landing-and-takeoff (LTO) cycle and between surface and 3,000 ft have been used for surface air quality analysis. Aircraft emissions within the LTO cycle are addressed by the emission standards established by the International Civil Aviation Organization (ICAO) for aircraft engines, which are made more stringent as technology advances. A recent scientific study suggested that non-LTO aircraft emissions also contribute to surface air quality degradation (*10*). However, more studies are needed to develop a reliable understanding and estimates of impacts of cruise aircraft emissions on surface air quality.

There are currently no known ways to strictly determine from monitoring networks whether pollutants measured in the atmosphere are due to aviation or instead due to other sources, increasing the difficulty of determining how much of air quality degradation is due to aviation. Current scientific knowledge indicates that, once emitted, aviation emissions evolve and transform in a similar way as those from other sources and are indistinguishable from those present in the background air. However, ongoing research is investigating whether aviation has a unique "signature" that can distinguish it from other air pollution sources (*11*). Air quality impacts of air pollutants, including hazardous air pollutants (HAPs) released from any source, encompass a host of issues ranging from the characterization and magnitude of direct emissions to their ultimate fate via atmospheric transport and transformation into secondary air pollutants. Continued advancement is critical toward robust understanding of these issues for proper characterization of the magnitude and extent of changes in air quality and health impacts associated with aviation emissions.

The research needs associated with greenhouse gas and climate change, alternative aviation fuels, and modeling tools are addressed in other sections of this circular.

CURRENT STATE

As described earlier, the United States launched a 25-year plan for the Next Generation Air Transportation System (NextGen) under the auspices of the multiagency Joint Planning and Development Office (JPDO), which includes the Department of Transportation, FAA, NASA, Department of Defense (DOD), Department of Commerce, Department of Homeland Security, and White House Office of Science and Technology Policy. NextGen involves an integrated effort to ensure that the future air transportation system meets air transportation security, mobility, and capacity needs while reducing environmental impacts. The JPDO structure includes an Environmental Working Group that is addressing strategies to reduce aviation's impacts on air quality in absolute terms as it identifies research and development needs that will enable advanced modeling capabilities for predicting such impacts, as well as interrelationships with noise and climate impacts. Specific research and development activity needs and schedules are summarized in the *NextGen Integrated Work Plan: A Functional Outline* (http://www.jpdo.gov/newsArticle.asp?id=103) (*12*).

Research activities on aviation emissions and their air quality and health impacts are being pursued in various institutional settings, including federal and state governments, universities, and private consulting firms. Most of the federally funded, aviation-related emissions and air quality research, as well as health impacts research, is carried out by the FAA-NASA-Transport Canada sponsored center of excellence, the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) and the Airport Cooperative Research Program (ACRP), which is managed by the Transportation Research Board (TRB).

FAA, in coordination with other federal agencies, industry, academia, state organizations, and public interest groups, has developed the Aviation Emissions Characterization (AEC) Roadmap. Formerly known as the Particulate Matter (PM) Roadmap, coordination activities under the AEC Roadmap have been extended to include research activities on all aviation emissions and their environmental impacts. An annual meeting is convened to discuss the AEC Roadmap and a report of the meetings findings is published on the status of national and international research activities and major accomplishments. During the meeting, discussions take place to identify major gaps and uncertainties and also to prioritize the future research agenda. Related to the Roadmap was the development of the First Order Approximation (FOA) to estimate PM emissions from aircraft engines. Currently, Version 3.0 of the FOA is incorporated into the FAA Emissions and Dispersion Modeling System (EDMS) Version 5.1 (http://www.faa.gov/about/office_org/headquarters_offices/apl/research/science_integrated_modeling/media/(AEC)Roadmap_20081205.pdf).

- Understanding and quantification of aviation PM emissions is the utmost priority before using this information for characterization of the impacts of these emissions on the ambient air quality. FAA and NASA, along with several other agencies, such as DOD and EPA, have funded and participated in several campaigns, such as the Experiment to Characterize Aircraft Volatile Aerosol and Trace-species Emissions, three separate Aircraft Particle Emissions Experiments (APEX), and the Hartsfield-Atlanta-Delta Study on characterization of emissions from aircraft equipped with a modern fleet of engines. The Hartsfield-Atlanta-Delta Study was prepared under the PARTNER program. An ACRP study also summarized and interpreted aircraft gaseous and particulate emissions data from the APEX and Hartsfield-Atlanta-Delta studies (http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_009.pdf) (*13*). In addition, the NASA-sponsored Alternative Aviation Fuel Experiment characterized the emissions characteristics of engines burning several alternative aviation fuels, through the joint efforts of a variety of stakeholders. The first campaign was completed in 2009 and a second campaign is currently being planned.
- Previously, speciation profiles of aircraft hydrocarbon (HC) emissions were based on a single commercial aircraft measurement reported by Spicer et al. (*14*). Recently, FAA and EPA joined efforts to revisit the hydrocarbon emissions data representative of various aircraft and engine combinations collected during the APEX campaigns. This effort led to updated creation of a hydrocarbon speciation profile for jet engine–equipped commercial aircraft (*15*). This speciated HC emission profile also led to updates of known gaseous emissions of HAPs. This new profile now has only 17 known HAPs, and emission indices of key HAPs are generally lower than those included in the earlier profile included in the EPA SPECIATE database. This

newly developed data set on speciated HC emissions has been included in the EDMS model versions 5.1 and onward and is being used in air quality modeling and analysis projects funded by PARTNER and ACRP. Note that this speciated HC emission profile accounts for only 72% of the mass of total HC emissions. Nevertheless, this has been an important development in the characterization of aircraft emissions. FAA and EPA have also jointly released guidance on quantifying speciated organic gas emissions from airport sources (*16*).

- Since the release of the 2005 update of this chapter in the *Critical Issues in Aviation and the Environment* e-circular, progress has been made on multiple fronts. Recently ACRP has published two key reviews of the state of knowledge and research needs associated with aviation-related hazardous air pollutants (http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_007.pdf) and particulate emissions at airports (http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_006.pdf) (*17*, *18*). Ongoing projects, including *Measurement of Gaseous HAP Emissions from Idling Aircraft as a Function of Engine and Ambient Conditions* (ACRP 02-03A) and *Guidance for Quantifying the Contribution of Airport Emissions to Local Air Quality* (ACRP 02-08) are addressing aircraft idling emissions and development of guidance material to combine modeling with field measurements to comprehensively assess airport air quality concentrations, including chemically reactive pollutants.
- PARTNER Project 15 has published a study on the nationwide air quality impacts of aircraft LTO emissions (*19*). Following a well-matured risk assessment methodology, also recommended ICAO's Committee on Aviation Environmental Protection (CAEP) workshop on the impacts of aviation emissions, this study provided the first estimates of nationwide health risk exposure from aircraft. Initial results from this study, which have been presented at various conferences and symposiums, indicate that most of the "incremental" health impacts are due to particulate matter as a result of direct emissions of nonvolatile PM and secondary formation of volatile PM from aircraft NO_x, SO_x, and hydrocarbon emissions. Other PARTNER projects carried out the airport-specific aircraft emissions and health impacts study and concluded that the results are consistent with the PARTNER-15 study. PARTNER Project 11 also performed a study that concluded that overall incidences of premature mortality due to aircraft LTO-related HAPs and ozone changes are relatively insignificant as compared to those due to total PM. The study assessed emissions, the emissions-to-exposure relationships, and the toxicities for each of the three types of pollutants, with a focus on total population mortality risk in the several hundred kilometer vicinities around a few airports in the United States. Mortality risk was found to be dominated by PM; mortality risk from HAPs was generally several orders of magnitude lower, and aircraft emissions were found to reduce ozone concentrations in the study area (*20*).[2] The PARTNER-11 and PARTNER-15 studies also concluded health risk exposure to aircraft LTO-related PM, which for any air pollutant is a product of change in ambient concentration, toxicity, and population distribution, could extend as far as 300 km from the source regions and is consistently dominated by the volatile PM.
- Another PARTNER project is exploring whether the usage of ultra-low sulfur (ULS) aviation fuel (with sulfur concentrations below 15 parts per million) could reduce the negative impacts of aviation on air quality and human health. Through the cooperation of multiple universities, this project will feature a detailed environmental cost–benefit assessment of ULS fuel usage, using a variety of computational models (*21*).

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[2]Ozone formation is the product of complex chemical reactions mainly involving the ozone precursors NO_x and VOCs in the presence of sunlight. Under certain conditions it is possible for increases in an ozone precursor (e.g., increased NO_x due to the presence of aircraft) to reduce ambient ozone concentrations.

- With an eye toward reducing emissions, as well as noise and fuel burn, PARTNER sponsored a demonstration of the feasibility of using the Optimized Profile Descents (OPD) for multiple aircraft arrivals at Louisville International Airport. The results were positive in that reductions of emission, noise, and fuel burn were achieved, leading to several commercial airports developing specific OPD approaches. Approach and departure procedure types with reduced environmental impacts are an area of continuing research.
- The aviation community—including government agencies (FAA, EPA, and NASA), industry (manufacturers, airports, and airlines), academia, and professional organizations—is planning to continue and possibly augment efforts to develop better ways of measuring PM and HAPs, as well as improved methods to model various aircraft emissions. For example, the Society of Automotive Engineers (SAE) committee on Aircraft Exhaust Emissions Measurement (E-31) is developing methods for measuring PM emissions from jet engines. In addition, the SAE committee on Aircraft Noise and Emissions Modeling (A-21) has recently developed Aerospace Information Report 5715, a guidance document to clarify the different aircraft gaseous and PM emissions modeling methods.
- In support of the Aeronautics Research Mission Directorate, NASA Research Announcements solicit research proposals for projects under the (*a*) Fundamental Aeronautics Program, (*b*) Aviation Safety Program, (*c*) Airspace Systems Program, and (*d*) Aeronautics Test Program. Under these programs, several aircraft emissions and air quality–related projects are currently ongoing. Examples include emissions assessment of future aircraft technologies under the Fundamental Aeronautics Program and the assessment of local and system-level emissions under the Airspace Systems Program to determine the impacts of introducing new aircraft into NextGen for different future years. This includes the continued assessment of new technologies and operation measures to reduce emissions from both subsonic and supersonic aircraft.
- FAA's Continuous Lower Energy, Emissions, and Noise program will demonstrate new technologies, procedures, and sustainable alternative jet fuels that are intended to reduce the negative impact of aviation on air quality, noise, and the climate. Five-year agreements were awarded to five companies to develop and demonstrate a variety of impact-reducing pathways by 2015 (*22*).

Several state and local regulatory agencies have conducted ambient air quality studies at airports across the country. These studies lay the groundwork for future ambient studies that could potentially focus on apportioning the airports' contributions to local air quality.

- The Rhode Island Department of Environmental Management, with support from the Rhode Island Department of Health, conducted monitoring studies at T.F. Green Airport, which is located in Warwick and serves the Providence region. Various organic compounds and carbonyls, as well as black carbon and $PM_{2.5,}$ were measured at four locations around the airport and at a fifth location some distance from the airport. The findings indicated that correlation of most pollutants with airport operations or activity could not be made. However, elevated levels of black carbon were correlated with wind directions, indicating the airport could be a substantial source of black carbon.
- The New Jersey Department of Environmental Protection contracted with Environ to conduct monitoring studies around the Teterboro Airport. Monitoring locations were established at each end of two runways (four stations), and an Open Path Differential Optical Absorption Spectroscopy system was placed near the north end of the primary runway. Measurements of

most pollutants were not conclusive with regard to correlation with airport activity. However, measurement of ultrafine particles (UFPs) did show correlation with aircraft movement along the nearby taxiway and runway.

- The South Coast Air Quality Management District conducted measurements of black carbon and lead at Santa Monica and Van Nuys general aviation airports in California. Results indicated that elevated lead concentrations at the runway ends were substantially higher than the monitors located further from these airports. Because lead is still used in aviation gasoline, the source appears to be avgas-fueled piston aircraft.
- The California Air Resources Board funded a study conducted by the University of California, Los Angeles at Los Angeles International Airport (LAX) to measure $PM_{2.5}$, HAPs, black carbon, and UFPs at the blast fence and in the community downwind of the southern departure runway at LAX (*23*). The study findings indicated that peak $PM_{2.5}$ and HAPs were not well correlated with aircraft activity. However, black carbon and UFPs were correlated with aircraft activity when measured at the blast fence, and the size distribution of UFPs measured in the community fell between those measured at the blast fence and those measured at an upwind location not substantially affected by airport activity.

FUTURE VISION

The means to understand, quantify, and mitigate aviation emissions of traditional criteria pollutants, as well as pollutants of more recent concern (such as PM, HAPs, greenhouse gases, and diesel emissions from aviation ground service equipment), must be continually developed. There is also a need to conduct the studies required to scientifically assess health risks—first to human beings, and then to other sensitive organisms—from aviation emissions. Improved tools are needed to aid in communicating the conclusions of such studies to the general public.

RESEARCH NEEDS

Characterization, Quantification, and Communication

- Continue improving emissions quantification techniques, tools, and the associated data for airport sources.
- Improve the understanding and modeling of pollutant concentrations around airports, including prevalent species and factors affecting the concentration levels.
- Improve and assess the need to evaluate health risks associated with exposure to airport-generated pollutants.
- Begin summarizing available emissions data regarding specific airport sources that could be used to determine an airport’s contribution to local and regional air quality.
- Determine the most important airport sources contributing to on-airport and off-airport exposure.
- Develop a more reliable understanding of the impacts of cruise aircraft emissions on surface air quality.
- Conduct studies to improve the understanding of emissions occurring from aircraft low power conditions (taxiing and idling).

- Conduct uncertainty assessments to better understand the accuracy of modeled emissions, concentrations, and health risks. Develop methods of effectively communicating to the public the ranges of uncertainty in current modeling tools.

Mitigation

- Conduct research on new aircraft engine technologies to understand their emissions reduction potentials and the trade-offs between emissions, noise, and fuel consumption, as well as the interplay among the various pollutants.
- Conduct research to optimize reductions in noise, emissions, and fuel burn through operational measures including continuous descent arrivals, airport surface movement optimizations, etc.
- Research the emission reduction benefits of ultra-low sulfur fuel, alternative fuels, and additives.
- Begin research on reformulated aviation gasoline to remove lead.
- Continue the study of other mitigation techniques to aid in the development of emission reductions, and evaluate such mitigation measures relative to operational, environmental, and economic consequences.

Needs Specific to PM and HAPs

- Determine the effects of ambient conditions on PM and HAPs emissions.
- Better understand the actual thrust levels used by aircraft during idle and taxi conditions and determine the corresponding actual PM and HAPs emission rates.
- Fill in the key data gaps in the aircraft emissions estimation database for both PM and HAPs. Develop and maintain publicly available databases from peer-reviewed emissions data collected from the exhaust plume of a small sample population of aircraft engines running at idle and increasing to maximum rated power. The aim for testing these various engine types and sizes within the sample population is to develop a data set that represents the national fleet.
- Continue to collaborate with SAE E-31 and other stakeholders, including ICAO CAEP, to develop a detailed aircraft engine emissions measurement protocol for particulate matter that will provide consistent and validated methodologies to acquire accurate aircraft engine emissions data.
- Continue working with stakeholders such as NASA, FAA, EPA, academia, and industry to collect and analyze PM and HAPs data. To date, FAA has worked with the aviation community to collect emissions data from a growing sample of specific aircraft engines at several airports in the United States. Currently, FAA and others have accumulated enough data and information to begin a review of critical needs, such as information gaps, and how these needs can be addressed from the available information.
- Develop PM emission characterization studies for other airport-related sources, such as ground service equipment, auxiliary power units, and aircraft tires and brakes.
- Develop studies to fill in knowledge gaps between PM emissions from aircraft engines and other airport sources and the evolution of PM size, chemistry, and characteristics in downwind communities.

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Climate Change and Adaptation

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Policy makers at the international, national, regional, and local levels are paying increasing attention to the effects of anthropogenic (human-made) activities on the earth's climate. Human activities have increased atmospheric concentrations of greenhouse gases (GHGs), which are thought by most atmospheric scientists to increase global temperatures and have other effects on regional and local climate. Aviation operations are among the many anthropogenic activities that result in GHG emissions, such as carbon dioxide (CO_2), primarily from combustion of carbonaceous fuels in aircraft engines. For example, the United Nations Intergovernmental Panel on Climate Change (IPCC) estimated that fuel combustion for aviation contributes approximately 2% to the total anthropogenic CO_2 emissions inventory, and, if left unmitigated under very optimistic aviation growth scenarios, this could grow to as much as 4% by 2050.

A substantial amount of research is being conducted concerning the contribution of aircraft emissions to climate change on a global scale. This paper focuses on nonaircraft emissions, emissions inventories on local scales for regulatory or other purposes, and the role of airports in reducing emissions and facilitating adaptation of air transportation infrastructure to changing climatic conditions. Airports have been subject to increasing demands to reduce emissions on the local level and to be prepared for the effects that climate change may have on their infrastructure and airspace.

This section outlines the current state of knowledge and the types of research needed to better understand the climate change issues that are specific to airports, including evaluation of the potential effects of climate change on airport planning and maintenance. Research and debate about the rate of climate change, the human activities that are most responsible, and the human activities that should bear the brunt of required reductions undoubtedly will continue for many years, however most policymakers and the scientific community generally agree that anthropogenic activities are stimulating climate change throughout the world. The effects of climate change are measurable today in certain parts of the world and are anticipated to further materialize over the course of the next decade.

Aircraft generate the substantial majority of air travel–related GHG emissions. For example, the 2006 Seattle-Tacoma International Airport GHG inventory found that more than 90% of total CO_2 emissions associated with that airport were from aircraft operating above 3,000 feet.

The NextGen Joint Planning and Development Office has been working over the last few years to identify and address research needs associated with the contribution of aircraft to climate change through the Airport Climate Change Research Initiative (ACCRI). ACCRI has published reports, white papers and peer-reviewed journal articles regarding a range of critical issues on the effects of aircraft on climate change. General areas of uncertainty and research identified include

- Contrails and induced cirrus clouds,
- Chemistry and physics in the upper troposphere and lower stratosphere relevant to aviation, and
- Metrics that will best address emissions from aviation with differing temporal and geographic scopes.

Because of the detailed assessment of the current state of research and future needs that ACCRI has developed relating to the basic science associated with the effects of aviation on climate change, readers are encouraged to review the ACCRI publications listed in the sources section at the end of this chapter.

While increased attention is being paid to improving knowledge regarding the effects of aircraft operations on global climate, there are also critical research needs at the airport level. Increasingly, airports are being called upon by state and local governments to provide inventories of GHG emissions and to reduce emissions from sources under their control. Nonaircraft sources of GHGs at airports generally include: combustion of petroleum-based fuels in ground access vehicles, ground support equipment, and facility electrical power generation; consumption of cement in new construction; and waste incineration, fire training, and other maintenance and operations activities.

Relatively little research has been conducted concerning the effects of climate change on the air travel industry, specifically the airports that support this industry, or how airports are adapting or can adapt to these changes. The U.S. air transport system was stressed by the growth in demand for air travel over the past decade and the inability of the system to respond when needed with expansion at capacity-constrained airports and modernization of the air traffic system. This stress has been particularly evident during poor weather conditions, when the arrival acceptance rates at many airports are radically reduced, often resulting in systemwide delays. While growth in aircraft operations has been affected by recent economic conditions, FAA is projecting a return of growth in commercial and other aviation.

While predicting climate changes on a local or regional level is not precise, most analyses indicate the frequency and severity of weather events will increase in many areas. As the climate changes, changes in precipitation—in some areas, an increase in rainfall, and in others, drought—are also to be expected, according to the U.S. Department of Transportation and U.S. Global Climate Research Program. These changes in weather regimes could further burden already stressed airport and airspace capacity in some locations and might increase aggregate delays. Such changes also may affect the performance of stormwater management and other airport systems (such as the need for increased detention or adverse effects on pavement longevity). In many locations, it is anticipated that changes in the freeze–thaw cycle could affect pavement integrity (with negative effects in some locations and positive effects in others).

These types of conditions could impact the operational efficiency of the air transportation system and could influence airport facility requirements, such as stormwater detention capacity and pavement inspection and maintenance programs. Most of the airport facilities, infrastructure, and operations being planned today use 10-year and 15-year planning horizons. While future climate change impacts are uncertain generally, and specific impacts to the aviation industry at specific locations less certain, the industry has identified a need to remain aware of the latest developments and predictions regarding climate change impacts and consider how those predictions may impact aviation. Specific steps include understanding the latest climate predictions and their level of accuracy, linking with broader efforts to consider climate change adaptation, and considering how the industry as a whole could effectively address potential, but uncertain, climate impacts without expending limited available resources on scenarios that may not materialize. To prepare for future needs, the airport community is beginning to plan for the most probable near-term effects of climate change now.

CURRENT STATE

While there has been extensive research on climate change in general, there are still gaps in our ability to model and quantify GHG emissions from airport sources and their potential effect on global climate. Similarly, relatively little work has been done to articulate and identify problems that could arise from the effects of climate change on airport facilities and operations.

Regional and Local Assessment of GHGs and Their Effect on Climate Change

Under international treaties, GHGs currently are addressed at a national level. However, states, cities, and counties across the United States have begun to take action, responding to local political pressure, state legal requirements, and the perceived lack of action at the federal level.

A variety of state and local programs are being implemented to quantify GHG emissions and establish goals for emission reductions. Many of the inventory approaches use methods that differ from IPCC protocols. As a result, state and local aviation GHG emission inventories vary widely in format and results, primarily due to the varying methods and assumptions used to quantify emissions.

As noted above, research concerning aircraft-related GHG emissions, their quantities, and their potential contributions to global climate change is ongoing. Airport emission sources include emissions associated with generating electricity, incineration, aircraft rescue and fire fighting training, heating/ventilation/cooling, and ground vehicle and other combustion engine operation and fueling. However, modeling of nonaircraft GHG emissions in the airport setting has lagged behind modeling for other regional sources. In the past decade, FAA has assumed responsibility for accurate modeling of airport-related air pollutant sources, with the development and enhancement of the Emissions Dispersion Modeling System (EDMS) and the Aviation Environmental Design Tool. While EDMS Version 5.1 estimates CO_2 emissions from aircraft, it does not presently enable all airport sources to be evaluated.

A project funded by the Airport Cooperative Research Program (ACRP), *Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories* (ACRP Report 11), was released in 2009 and provides guidance for developing consistent airport-level GHG emissions inventories. The guidebook addresses recommendations regarding which pollutants to model, what emission rates and metrics to use, how to geographically allocate emissions, and how to avoid double-counting.

The public has access to numerous carbon calculators on the Internet that claim to assess GHG emissions associated with an individual flight. These calculators generally focus only on aircraft-related emissions and do not reflect other emissions related to the air travel experience, such as those from airport stationary sources, ground travel to the airport, and the ground vehicles that service the aircraft. Many of these calculators include a radiative forcing index to compensate for non-CO_2 effects of aircraft travel in the upper atmosphere. These methods are not consistent with each other, nor are they consistent with other subnational, national, or international assessments of aviation-related GHG emissions.

State of Current Research on the Effects of Climate Change on Airports

Climate change has the potential to affect land use and infrastructure, as well as aircraft operations, and might also affect the ability of airports and the U.S. airspace to efficiently handle expected increases in demand, as well as the means by which they do so. However, the effects of climate change have not been studied in detail to date, thus no metrics or modeling standards for predicting how these changes may affect specific airports exist. This information will be important as efforts are undertaken by FAA, airports, and other stakeholders to provide and preserve airport and airspace capacity to meet future demand.

No research has been identified that systematically considers the effects of climate change on the air transportation system infrastructure or operational efficiency, beyond relatively simple assessments of impacts associated with potential flooding of infrastructure at or just above sea level. Substantial disagreement exists concerning exactly how global, regional, and local climates will evolve with increasing atmospheric levels of GHGs. On a global level, these differences primarily relate to the degree to which mean global temperature will change. On a regional or local level, climate change may lead to increases or decreases in precipitation, more severe weather events, shifts in seasonal weather patterns, and varied changes in temperature.

Under some scenarios, it is predicted that sea levels would rise and could inundate the infrastructure of many coastal cities. Since many airports are located on or near bodies of water, they may be vulnerable to even minor changes in sea level. A significant increase in sea levels could also have effects in redistributing populations throughout the country, affecting aviation demand patterns.

Increases in the frequency and severity of poor weather could reduce the ability of airports to handle flights under visual flight rules, which can reduce the arrival acceptance rate at many airports.

Stormwater and adverse local air quality impacts also are anticipated. Research indicates there is likely to be an increase in average annual rainfall or the size of peak rainfall events at many locations, potentially affecting the sizing and design of stormwater detention facilities. Other locations may experience drought conditions. Researchers have noted the likelihood of further degradation in local air quality as climate changes occur. For instance, as temperatures rise and populations increase, many cities anticipate that air quality in some locations will exceed the national ambient air quality standards, or that the frequency and duration of such exceedances will increase, which in turn will necessitate increasing emission control requirements on sources that contribute to local air quality problems, including air travel–related emission sources.

While research is needed to more precisely define possible implications for aviation infrastructure, they might include

1. Higher wind velocities that could damage structures, require tie-downs for larger aircraft, and inundate coastal areas with storm surges;
2. Higher average temperatures that could affect material specifications, require longer runway lengths or reduced take-off weights due to compromised aircraft performance, and increase the risk of forest fires and dust storm events that can reduce visibility;
3. Invasive species that could affect landscaping and maintenance practices;
4. Increased designations of endangered species that may affect infrastructure development; and
5. Effects on permafrost and other unique environments.

These factors in turn may result in changes in insurance and lending policies that could impact financing costs, public expectations, and the timing and feasibility of airport infrastructure investments. In addition, climate change may affect underlying demand at many airports, especially airports that rely on climate-dependent tourism, such as skiing and beach resorts.

Consideration of these potential impacts is likely to become part of airport planning for future capacity and infrastructure needs. In recent draft guidance regarding the National Environmental Policy Act, the White House's Council on Environmental Quality has recommended federal agencies consider the effects that climate would have on proposed federal actions, as well as the effects that federal actions would have on climate. This may become especially important at airports potentially subject to coastal or other flooding or dependent for their demand on activities that may be affected by climate change, such as skiing. It also may be important to the assessment of specifications for projects, such as runway length or stormwater detention capacity.

Because of the initiatives of state and local climate action plans, demands on airports for GHG emission reductions are likely to increase. Airport operators, which only own and control a small percentage of the sources associated with these emissions, will be asked to implement mitigation measures. For instance, the City of Los Angeles' Climate Action Plan mandates a 35% reduction in GHG emissions relative to 1990 levels. Research also would provide better guidance concerning the range of actions that can be undertaken to reduce emissions without adversely affecting the aviation industry.

RESEARCH NEEDS

Airports, states, local governments, companies, and others need adequate tools to conduct local and regional GHG emissions inventories to support informed decision making and transparency. Such tools should be comprehensive, user-friendly, and consistent with each other and with other inventory tools.

Building on the current state of knowledge and research into the effects of aviation-related GHGs on climate change, research into the role of airports as a source of GHG emissions and into the effects of climate change on airports is needed to inform and support aviation-related policy and decision making. This research will foster a better understanding of the potential economic, design, technology, or operational trade-offs of any control strategies.

Note that many of these questions raise issues that are not unique to aviation or airports. Research should take advantage of information developed for other transportation modes and activities. Specific research topics include the following:

- Follow-up research to ACRP Report 11, *Guidebook on Preparing Greenhouse Gas Emissions Inventories*, regarding the standardization of aviation-related GHG and climate change assessment methodologies for use on a subnational or airport-specific level.
- Inclusion of nonaircraft sources in consistent, scalable tools to enable the evaluation of air travel–related emissions.
- Identification of anticipated regional climate changes, associated weather patterns, and anticipated timing of such climate change, along with the effects of such changes on aviation and aviation facilities, such as airports.
- Analysis of the effects that changes in air quality associated with climate change will have on airports, their need to mitigate emissions, and their ability to develop infrastructure.
- Development of tools to predict changes in population patterns as a result of climate change and how the changed population patterns might affect demand for air travel.
- Effects of possible changes in climate on demand at airports resulting from impacts on tourism and other economic activities.
- The anticipated effect of climate change on airport operations, such as instrument flight rules versus visual flight rules, take-off weight limitations, reliance on satellite navigation, and changes in capacity and aircraft separation.
- The cumulative effect of operational impacts related to climate change on the national airspace system.
- Identification of airport infrastructure and procedures that could be affected by predicted regional effects of climate change, such as changes in precipitation volume, frequency, type, and intensity; changes in temperature gradients and wind velocities; changes in vegetation cover and habitat; and changes in the patterns of aviation system demand. This could include stormwater management, snow clearing and storage, airfield and aircraft deicing, runway length requirements, aircraft tie-downs, and ground-cover management, such as requirements for dust control and wildfire management.
- Research into technologies, airport layouts, and operational approaches that would reduce GHG emissions from nonaircraft sources at airports.
- Consideration of alternative methods in airport construction to reduce GHG generation.
- Consideration of the ability of alternative pavement materials to withstand possible effects associated with climate change.
- Development of methods to quantify the monetary value of potential aviation-related climate effects for use in assessing trade-offs and market-based measures.

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Water Quality

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Operations and development activities at airports have the potential to affect a variety of water resources, as summarized in Figure 1.

Over the past two decades, interest in and concern over the potential impacts of airport operations on water resources have increased as environmental regulators look beyond the more obvious sources of water pollution, such as end-of-pipe industrial waste discharged into large water bodies, and attempt to address issues such as stormwater run-off and nonpoint sources. Airports, which typically include large areas of impervious surfaces and host activities that can generate discharges of potential contaminants, such as vehicle and aircraft fueling, maintenance, and deicing, have been subject to the requirements of the federal Clean Water Act for almost two decades, but the application of these rules to the unique operating environment of airports continues to be refined. In recent years, new issues have emerged, such as managing wildlife attractants and the unanticipated impacts of "environmentally-friendly" airfield pavement deicers on aircraft and airfield infrastructure.

	Potentially Affected Water Resource					
	Stormwater	Potable Water	Water Supplies	Groundwater	Wetlands	Aquatic Communities
Facilities planning and design	✔	✔	✔	✔	✔	✔
Operations & maintenance	✔	✔	✔	✔	✔	✔
Public health		✔	✔			
Conservation/sustainability	✔		✔	✔		

FIGURE 1 Activities and potentially affected water resources.

The relationship, and occasional tension, between protecting the environment and protecting the safety of the traveling public is present in the water resources context in several critical areas.

CURRENT STATE

Aircraft and Pavement Deicing and Anti-Icing

- Environmental Impact of Deicing and Anti-Icing Agents: Deicing and anti-icing agents, used to ensure safe operations in freezing temperatures or other conditions in which frost may form on pavement or aircraft surfaces, may have environmental impacts. Although some questions have been raised about potential releases of air emissions from deicing agents, most attention has been focused on the potential for deicing agents to become entrained in stormwater and carried through the storm sewer system into nearby bodies of water. The potential impacts of these agents to receiving waters of greatest concern are reduced dissolved oxygen because of rapid biodegradation, aquatic toxicity from additives required to achieve performance certification, and eutrophication (i.e., nutrient enrichment).

The U.S. Geological Survey (USGS) conducts research on the environmental impacts of deicers in airport discharges. Ongoing research topics include characterizing environmental conditions during deicing discharges, partitioning biochemical oxygen demand (BOD) in airport stormwater discharges by source, quantifying the amounts of Type I and Type IV deicers in airport stormwater discharges, evaluating the toxicities of new deicers, and identifying conditions associated with the occurrence of bacterial biofilms in surface waters receiving deicing discharges.

The Airport Cooperative Research Program (ACRP) also published research into alternative aircraft and airfield deicing and anti-icing formulations with reduced aquatic toxicity and biological oxygen demand. The research aimed to identify promising alternative fluid formulations with reduced aquatic toxicity and BOD and to evaluate the performance, efficiency, material compatibility, and environmental, operational, and safety impacts of these alternative formulations compared with current commercial products. (*ACRP Research Results Digest* 9: *Alternative Aircraft and Pavement Deicers and Anti-Icing Formulations with Improved Environmental Characteristics*; *ACRP Web-Only Document 3: Formulations for Aircraft and Airfield Deicing and Anti-Icing: Aquatic Toxicity and Biochemical Oxygen Demand*; *ACRP Web-Only Document 8: Alternative Aircraft Anti-Icing Formulations with Reduced Aquatic Toxicity and Biochemical Oxygen Demand.*)

- Optimization of Deicing Fluid Usage: Continued improvements in deicing technology and application have reduced the volumes of deicing agents used while ensuring safe aircraft operations. The technology for collecting run-off from aircraft deicing operations has stabilized, with most developments being refinements of existing techniques and approaches. Much of the current technological development is on improved deicing products with better performance and reduced environmental implications.

ACRP is about to publish research (*ACRP Report 45: Optimizing the Use of Aircraft Deicing and Anti-Icing Fluids*) that identifies procedures and technologies that optimize the use of aircraft deicing and anti-icing fluids, thus reducing their environmental impact while assuring safe aircraft operations in deicing and anti-icing conditions.

- Corrosivity of Pavement Deicers: The Society of Automotive Engineers' International Aerospace Division G-12 Aircraft Ground Deicing Committee develops standards and recommended practices in the area of aircraft and airfield pavement deicing. A G-12 subcommittee is investigating the impact of certain airfield pavement deicers on corrosion of cadmium-plated components and shortened service life of carbon–carbon brake components as a result of catalytic oxidation. Current research is focused on standardized testing techniques to characterize the effects of deicers on brake components.

ACRP Synthesis Report 6: Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure documented how airports deice their airfield pavements, chemicals used, amounts applied, and evidence of associated corrosion or degradation of aircraft and airfield infrastructure.

- Proposed Deicing Run-Off Regulations: In 2004, the U.S. Environmental Protection Agency (EPA) identified airport deicing operations as candidates for the development of a technology-based effluent limitations guideline (ELG). Data collection for this effort, including questionnaires directed to key industry sectors and site visits to airports, was commenced by EPA in 2005 and continued through 2007. The agency published for public comment a proposed ELG on August 28, 2009 containing the following components:
  - For all primary airports with 1,000 or more annual scheduled commercial air carrier jet departures, either an elimination of the use of urea-based deicers or a numeric limitation on ammonia in airport stormwater discharges.
  - For all primary airports with 1,000 or more annual scheduled commercial air carrier jet departures and 10,000 or more total annual departures, a tiered glycol collection performance standard. For those airports with more than 460,000 gallons of "normalized" glycol used per year, 60% of available applied glycol must be collected. For airports where less than this volume of glycol is used, 20% of available applied glycol must be collected.
  - For airports where aircraft deicing run-off is collected and treated onsite for discharge to waters of the state, effluent discharge limitations for chemical oxygen demand (COD) in those discharges.
  - A New Source Performance Standard (NSPS) requiring collection of 60% of available applied glycol at new airports and in association with certain airfield improvements.

  The public comment period ended on February 26, 2010. Extensive comments were submitted by aviation industry associations and individual airports and airlines raising serious concerns about the technical basis and economic feasibility of the proposed rule. As of this writing, EPA has stated its intention to publish final rule in early 2011.

- Treatment and Recycling of Collected Aircraft Deicing Run-Off: Innovative technologies are being implemented at different airports for treatment or recycling of collected deicing run-off. Some examples include
  - Detroit Metropolitan Wayne County Airport maximizes loading rates of deicing discharges to its publically-owned treatment works (POTW) and minimizes risks of plant upset through close coordination with the plant to optimize nutrient balance (particularly phosphorus) in the treatment system.

– Denver International Airport's glycol recycling facility added a mechanical vapor recompression unit to allow processing of run-off with glycol concentrations as low as 1%, reducing the need for and cost of discharges to the POTW.

– Buffalo Niagara International Airport implemented an engineered wetlands system for treating deicing run-off that had previously been sent to a POTW.

– Dulles International Airport installed passive biological treatment units for the first flush deicing run-off from airfield pavement areas.

– Anaerobic fluidized bed treatment plants were installed at Albany County, Akron-Canton Regional, and Portland International Airports to treat concentrated deicing run-off.

- Managing run-off from aircraft and airfield deicing and anti-icing operations: ACRP published a report resulting in planning guidelines that incorporate an array of best management practices for the practical, cost-effective control of run-off from aircraft and airfield deicing and anti-icing operations (*ACRP Synthesis Report 6: Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure*). Another ongoing ACRP project (ACRP Project 02-14, Guidebook for Selecting Methods to Monitor Airport and Aircraft Deicing Materials) will result in a guidebook to help airports identify, compare, and select practical on-site methods (i.e., instruments, technologies, techniques, etc.) for monitoring deicing materials in water. Additional ACRP research (ACRP Project 02-19, Winter Design Storm Factors for Airport Stormwater Management) will result in the development of a guidebook for airport designers and operators to define the relevant winter storm design factors and how they should be considered in determining a winter design storm for the purpose of sizing and selecting a collection, conveyance, storage, and treatment system in the management of run-off from aircraft deicing operations.

Construction and Development Stormwater Run-Off

EPA promulgated a final ELG for the construction and development industry on December 1, 2009. The new ELG became effective for new permits for construction and development activity issued after February 1, 2010. Many construction projects on airport sites would be governed by these new requirements.

The final ELG established technology-based limitations for run-off from construction sites with greater than 1 acre of disturbed land area. These standards were divided into two classes: narrative best management practices (BMPs) and a single numeric limitation of 280 NTU for turbidity applicable at certain sites. The narrative BMPs would be effective immediately upon their incorporation into new permits. The turbidity limitation also was to be incorporated into all new permits, but would have been effective for sites at which 20 or more acres are disturbed at any one time beginning on August 1, 2011, and for sites at which 10 or more acres are disturbed at any one time beginning on February 2, 2014.

The final ELG, however, was subjected to judicial review and, in August 2010, EPA filed an unopposed motion asking the federal court to vacate and remand the ELG's numeric effluent limitation, and to remand the administrative record for further explanation by EPA. EPA requested an additional 18 months to better explain (or, perhaps, to revise) the numeric effluent limitation.

The unopposed motion also stated that the Agency "will also address any other issues that reveal themselves to the Agency on remand," leaving open the possibility that other provisions of the final rule might be altered. At present, however, it appears that the final ELG—other than the final numeric limitation—remains in effect and will be implemented as described above. Clarification of this point may be provided by any order issued by the court in response to EPA's motion.

ACRP is funding the development of a handbook (ACRP 02-11, *A Handbook for Addressing Water Resource Issues Affecting Airport Capacity Enhancement Planning*) for addressing water resource issues affecting airport capacity enhancement planning. The handbook will assist airport operators and planners as they identify and address issues and requirements relating to water resources (including quality and quantity, wetlands, and groundwater) that may affect the environmental review process linked to airport capacity improvements.

Postconstruction Stormwater Run-Off

EPA also has in process an initiative to enhance its stormwater regulations for the built environment. This so-called "development and redevelopment" stormwater rulemaking would pick up where construction permitting leaves off, addressing the run-off from built sites. EPA's intent is to publish a proposed rule for public comment by the end of 2011 and a final rule by the end of 2012.

The expected objective of this rulemaking is to ensure new developments and redevelopments do not alter the natural hydrology of the site. That is, rather than addressing pollutant concentrations or loadings, EPA appears to be focusing on ensuring the quantity and the intensity of run-off from the finished site are the same as they would have been from the site before development. According to EPA's early statements, this could be accomplished by use of "green infrastructure" techniques, including infiltration, evapotranspiration, or rainwater harvesting. Where such techniques are not sufficient, other, more traditional run-off control mechanisms might be acceptable and/or sites might be required to pay fees-in-lieu of complete control to their host municipal storm sewer system.

Many elements of this new rulemaking remain undecided. Will it apply only to newly constructed or redeveloped sites, or will existing facilities be required to retrofit? How much flexibility will there be to achieve run-off targets using more traditional, nongreen infrastructure run-off control technologies? Who will implement the new requirements—National Pollutant Discharge Elimination System permitting authorities or Municipal Separate Storm Sewer Systems—and how uniform will that implementation be?

Several key questions remain unanswered about the relationship of the new rule to the aviation community. Most significant, will it apply at all? It is clear the NSPS in the proposed airport deicing ELG addresses certain postconstruction run-off from portions of the airside of airports subject to proposed collection requirements. It is less clear, however, that the new rule—which EPA says will focus on quantity and intensity of run-off as opposed to its quality—is meant to establish a separate additional set of requirements for that same run-off. Similarly, it is unclear whether any retrofit requirements would be intended to apply to existing airport development— whether air- or land-side. Finally, to the extent airports are defined by large impervious surfaces, many of which cannot readily be replaced with pervious materials, would application of the contemplated rule amount to a mandate that airport authorities simply make substantial payments-in-lieu of achieving run-off reductions? Is this consistent with airport revenue diversion restrictions?

EPA and others have developed guidance materials that catalogue low impact design and green infrastructure practices. These include materials available on the agency's web pages on Low Impact Design and Green Infrastructure.

Wildlife Hazard Management

Many airports are located on or adjacent to various water resources, including open water and wetlands. These water resources provide habitats for myriad wildlife, many of which are protected by various federal and state laws. Enhancing and preserving the water quality of these habitats is an important goal of the Clean Water Act. At the same time, wildlife that utilize these water resource areas present hazards to aircraft, especially during approach or departures at altitudes of 2,000 ft or less, where more than 90% of aircraft-wildlife strikes occur. Although most of the attention is focused on birds, terrestrial macrofauna (most notably, deer) also account for a significant proportion of the wildlife hazards at airports. The incidence of aircraft–wildlife strikes is rising, attributable in part to significant improvements in the quality of these habitats, increased reporting of strike events, increasing populations of certain waterfowl populations, and increasing air traffic.

Many airports are located in close proximity to natural or man-made water resources that are not within the airport property boundary. FAA Advisory Circular, AC 150/5200-33B, *Hazardous Wildlife Attractants on or near Airports*, sets separation criteria guidance for wildlife hazard attractants (up to 5 miles from the airfield if the attractant would cause hazardous wildlife movement across approach or departure airspace). Airports are challenged with working outside of the airport property boundary within the separation criteria. The U.S. Department of Agriculture (USDA) Wildlife Services and FAA guidance provided to assist airports in the management of wildlife hazard attractants includes tools such as habitat modification, deterrent activities, exclusionary devices, and wildlife control. All these are options for managing off-site areas, but often these off-site water resource areas, not under the airport sponsor's control, are protected or regulated areas under government, nonprofit, or private control. Airports face challenges educating and coordinating issues related to wildlife hazards with off-airport land owners and managers and environmental agency staff that manage or regulate off-airport water resource areas. As an added complication, water resource areas can be associated with wildlife refugees, conservation areas, parks, and other protected or permitted areas that have their own set of environmental goals and requirements.

To help coordinate potential conflicts, FAA and five other federal agencies developed and signed a memorandum of agreement (MOA) in July 2003 formalizing the internal management of the agencies' approaches to dealing with potential conflict of aviation safety and wildlife. The development of coordination materials and guides for federal, state, and local-level conflict management could be useful for airports as they address on- and off-airport wildlife hazard attractants and off-airport incompatible land uses. It also would be beneficial for airports to have access to educational and outreach resources to work with environmental and permitting agency staffs, land owners, and local decisions makers to provide the background, regulatory setting, and issues related to aviation safety and wildlife. Currently, technology-based deterrent and exclusionary devices are being developed and utilized for mainly man-made water resource areas on airport. Further research and development of additional technology-based deterrent and exclusionary devices for natural area water resources should be pursued.

FAA, USDA, the U.S. Department of Defense, and various other stakeholders have invested significant resources to reduce aircraft–wildlife interactions in the airport environment. Much of this effort has focused on reducing the attractiveness of airport environs to wildlife through reduction of habitat features where problem wildlife feed, breed, and roost, or rest.

Water Conservation

For airports in regions where the availability and cost of water supplies are limited by diminished sources and increased demands, water use reduction is practical, economical, and an important social issue. As a result, airports are looking at ways to implement water conservation, an important sustainability measure.

The fundamental objective of water conservation is the same as in nonaviation contexts: minimizing usage through best practices. In most cases, best practices for airports are similar to those employed by municipalities, campuses, and other users.

In 2009, Airports Council International-North America's (ACI-NA) Board of Directors adopted this environmental goal on water conservation for its member airports: "By 2014, every ACI-NA member airport will strive to implement a water conservation program that includes adoption of an airport-specific goal to reduce water consumption."

ACI-NA identified the following components associated with achieving the goal:

- A water conservation plan that includes measurable goals, practices to be implemented to achieve those goals, responsibilities, performance monitoring, and a schedule.
- A benchmark of water usage against which future reductions can be measured.
- An achievable goal for reduction in water usage.
- Methods for tracking water usage and associated costs that support quantitative evaluation of the performance of conservation efforts against the defined goal.

FUTURE VISION

The aviation industry needs to encourage the development of programs to address the following specific aviation needs relating to water quality:

Aircraft and Pavement Deicing

- Cost-effective deicing products and practices that are consistent with protection of aquatic resources and compliance with environmental permits while maintaining a high level of aircraft safety.
- Practical treatment and recycling technologies for airports to manage collected deicing fluids.

Construction and Development Stormwater

- Implementation of new regulations, as they may be revised, in a manner consistent with unique demands of airport construction.

- Industry practices that satisfy all the new regulatory obligations associated with discharges from airport construction projects.

Postconstruction Stormwater

- Determine the prospective regulation's relationship to the proposed ELG for airport and aircraft deicing and anti-icing activities.
- Determine the impacts of limits on the volume and intensity of stormwater run-off to facilities, like airports, that require large areas of impervious surfaces and other surface features to safely and efficiently operate and that cannot readily be reengineered to maximize infiltration or evapotranspiration.

Wildlife Attraction

While not exclusively a surface water-driven problem, eliminate, minimize, and manage surface water resources at and around airports to continue efforts to reduce wildlife hazards.

- Airport operators continue to manage water-related wildlife attractants and wildlife activity in the operational areas of their airports.
- Airport sponsors work with other agencies to alert those agencies about land use decisions that could cause or worsen aircraft-wildlife conflicts.
- While civilian and military aviation agencies have devised and implemented many practical solutions to minimize aircraft-wildlife conflicts, continued efforts to address wildlife hazards require development of new innovation to achieve further safety enhancement.
- Maintain constant vigilance at all airports to reduce aircraft–wildlife conflicts.

Water Conservation

- Identify methods to quantify water usage.
- Implement water conservation plans at every airport.
- Establish industry metrics for setting goals and assessing progress of water conservation efforts.

RESEARCH NEEDS

To address current and future airport-related water quality issues, airport sponsors, agencies, vendors, and other stakeholders need to conduct research addressing the following topics:

Aircraft and Pavement Deicing

- Develop new aircraft deicing and anti-icing formulations with reduced BOD and improvements in other environmental characteristics.
- Research and develop new airfield pavement deicers with improved environmental characteristics and that do not damage carbon brake components.

- Develop and implement deicing technologies to further reduce usage of aircraft and airfield pavement deicers while maintaining safe operations.
- Determine the need for improvements in accepted methods for optimizing discharges of deicing run-off to municipal wastewater treatment plants.
- Develop practical recycling technologies capable of cost-effectively recovering glycol at concentrations less than 1%.
- Establish the basis for engineering solutions to address nontraditional impacts of deicing discharges to receiving waters.

Construction and Development Stormwater

Moving forward, the aviation community works with EPA to

- Confirm the feasibility of achieving numeric effluent limitations in the context of an airport construction project; and
- Identify any other issues reflecting airport-specific concerns and bring to EPA's attention. These latter may include evaluation of the following obligations in an airport context:
  - Stand-alone, secure, cost-effective systems to monitor turbidity in nephelometric turbidity units (NTU);
  - Relative merits of various NTU measuring technologies;
  - Autocalibration for NTU measuring instruments;
  - Establishment of practical limitations on monitoring sites;
  - The feasibility of performing phased airfield construction to ensure each construction phase disturbs less than 10 acres; and
  - Assessment and characterization of conditions that make a site a candidate for use of passive treatment and site conditions that make active treatment a more reasonable first choice.

Postconstruction Stormwater

While existing sources provide reasonable background information, additional resources may be necessary as EPA and possibly other regulatory authorities develop postconstruction run-off controls. Depending upon the content of the final rule, the airport industry likely will need a standard reference for the selection and use of postconstruction run-off management controls suitable for use by civil engineers when developing site designs. Even before this kind of final, implementation-focused resource is produced, research on the following subjects may prove valuable in the course of the rulemaking:

- Suitability of airports for regulation of quantity and intensity of run-off,
- Cost of mitigating run-off quantity and intensity if on-site measures cannot reasonably be implemented,
- Relative benefits of run-off reduction through vegetative means and use of native vegetation and other techniques to reduce or eliminate irrigation requirements, and
- Potential relationship between on-site vegetative run-off controls and wildlife hazards at airports.

Wildlife Attraction

- Innovative educational and outreach materials for communities and landowners to address off-airport water resource or other land uses (e.g., municipal waste facility, composting, or agricultural areas, etc.) that pose known wildlife hazard attractant management challenges.
- New techniques and technologies to reduce the attractiveness to wildlife of surface water resources in the airport environment.
- New technologies for detection of wildlife activity in the airport environment.
- Integration of wildlife movement detection, foreign object debris detection, and security surveillance systems.
- New techniques and technologies for deterring wildlife from frequenting or occupying airports where water resources cannot be eliminated (i.e., coastal airports, national wildlife refuges, and state and local protected water resource areas).
- New stormwater management planning, design, and maintenance methods to minimize wildlife hazard attractions on and around airports.
- New nonfederal land use management and regulatory tools (e.g., zoning) to reduce wildlife hazards on property surrounding airports.
- New approaches to integrate multijurisdictional water resource governance in the airport environment. Although FAA, the U.S. Fish and Wildlife Service, EPA, and U.S. Army Corps of Engineers agreed to avoid wildlife hazards under the terms of the July 2003 MOA, water resources are regulated by various states, counties and municipalities throughout the country. These layers of regulation sometimes conflict with FAA requirements and themselves, and may force design of project features or mitigation that pose wildlife hazards.

Water Conservation

- Industry guidance on planning water conservation efforts tailored to facility-specific context and needs.
- Established industry metrics for setting goals and assessing progress of water conservation efforts.
- Methods to quantify water usage.

RESOURCES

ACRP Project 02-01, Alternative Aircraft and Airfield Deicing and Anti-Icing Formulations with Reduced Aquatic Toxicity and Biochemical Oxygen Demand. http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=129.

ACRP Project 02-11, A Handbook for Addressing Water Resource Issues Affecting Airport Capacity Enhancement Planning. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2574.

ACRP Project 02-14, Guidebook for Selecting Methods to Monitor Airport and Aircraft Deicing Materials. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2785.

ACRP Project 02-19, Winter Design Storm Factors for Airport Stormwater Management. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2790.

ACRP Report 14: Deicing Planning Guidelines and Practices for Stormwater Management Systems. www.trb.org/Publications/Blurbs/Deicing_Planning_Guidelines_and_Practices_for_Stor_161758.aspx.

ACRP Report 45: Optimizing the Use of Aircraft Deicing and Anti-Icing Fluids. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=122.

ACRP Synthesis Report 6: Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure. www.trb.org/Publications/Blurbs/Impact_of_Airport_Pavement_Deicing_Products_on_Air_157067.aspx.

ACRP Web-Only Document 3: *Formulations for Aircraft and Airfield Deicing and Anti-Icing: Aquatic Toxicity and Biochemical Oxygen Demand*. www.trb.org/Main/Public/Blurbs/155765.aspx.

ACRP Web-Only Document 8: Alternative Aircraft Anti-Icing Formulations with Reduced Aquatic Toxicity and Biochemical Oxygen Demand. www.trb.org/Publications/Blurbs/163310.aspx.

Hazardous Wildlife Attractants on or near Airports. FAA Advisory Circular, AC 150/5200-33B, www.faa.gov/airports/resources/advisory_circulars/index.cfm/go/document.information/documentNumber/150_5200-33B.

Research Results Digest 9: Alternative Aircraft and Pavement Deicers and Anti-Icing Formulations with Improved Environmental Characteristics. www.trb.org/Publications/Blurbs/Alternative_Aircraft_and_Pavement_Deicers_and_Anti_163408.aspx.

SAE G-12 Aircraft Ground De-Icing Steering Committee. www.sae.org/servlets/works/committeeHome.do?comtID=TEAG12.

U.S. EPA Airport Deicing Effluent Guidelines. http://water.epa.gov/scitech/wastetech/guide/airport/index.cfm.

U.S. EPA Construction and Development Effluent Limitation Guidelines. http://water.epa.gov/scitech/wastetech/guide/construction/index.cfm.

U.S. EPA Development and Redevelopment Rulemaking. http://cfpub.epa.gov/npdes/stormwater/rulemaking.cfm.

U.S. EPA Guidance on Green Infrastructure. http://cfpub.epa.gov/npdes/home.cfm?program_id=298.

U.S. EPA Guidance on Low-Impact Design. www.epa.gov/owow/nps/lid/index.html#fact.

Aviation Alternative Fuels Development and Deployment

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Propelled by a combination of supply stability, security, and environmental concerns, commercial aviation has sharpened its focus on alternative fuels for aviation over the past 4 years. The challenges are being addressed through the focused and aligned efforts of the entire aviation supply chain, including airlines, airports, manufacturers, and well over a dozen government agencies led by the FAA Office of Environment and Energy and now more than 50 suppliers through the Commercial Aviation Alternative Fuels Initiative (CAAFI) in concert with the U.S. Department of Defense (DOD).

In the 5 years since the Transportation Research Board (TRB) committee on Environmental Impacts of Aviation focused on fuels issues at the 85th TRB Annual Meeting in 2006, the acceptance of the prospects for sustainable alternative fuels production have risen to the point where nearly 37% of biofuels producers now believe that 1 billion gallons of renewable jet fuel will be available by 2020 (*1*).

The progress of the industry was recognized on February 1, 2010 when *Air Transport World* bestowed their Joseph S. Murphy Award for Industry Service on CAAFI for successes in developing and initiating the deployment of aviation alternative fuels (*2*).

This paper highlights the issues that have been addressed to date and those that remain, including the substantial challenges that must be overcome to ensure future successes. While this chapter provides a detailed overview of the subject, it is recommended that readers consult the CAAFI website for both details on the definition of terms and the most recent progress and challenges in this rapidly emerging field (*3*).

BACKGROUND ISSUES AND SOLUTION METHODOLOGIES

In developing and adopting new fuels, the aviation industry has needed to address unique safety, operational, and environmental challenges. Issues associated with the broad range of aircraft operating conditions constrain the number of candidates to be examined in ways not experienced by other transportation modes. Operating at multiple altitudes presents multiple, and in some cases contradictory, directions to define the best environmental footprint. Any alternative fuel also faces large costs in creating feedstock, production, and distribution infrastructure. In the case of aviation, the unique airport-based infrastructure differs from other transportation modes. While aviation fuels produce unique technical challenges, aviation also must cope with the fact that it represents less than 10% of transportation fuel consumption and hence is seen as a minority player by energy suppliers.

Security of supply issues can be quantified by identifying the magnitude of expenditures needed to defend oil fields, well heads, pipe lines, and sea lanes that are required to protect the two-thirds of domestic needs currently obtained from offshore sources. According to DOD sources, this cost is as high as $50 billion to $130 billion annually, without accounting for any associated war costs.

Supply stability issues go beyond average price. These can be observed as both the frequency of price spikes and the magnitude of a refiner's price differential between crude oil and refined aviation fuel, known as the aviation crack spread. Information presented by the Air Transport Association illustrates crack spread for aviation fuel has tripled over the past few years. Localized price spikes also are more prevalent and include, but go beyond, Hurricane Katrina-like events in the Gulf of Mexico.

The emergence of alternative fuels for aviation adds three additional dimensions to emissions assessments. These come on top of the consideration of variances already seen in having to evaluate emission effects at varying altitudes ranging from local air quality around airports below 3,000 ft to issues of contrail formation at the highest flight altitudes.

First, modifications to the fuel content itself will alter outcomes predicted by such tools as the Emissions Dispersion Modeling System (EDMS). These will vary with fuel type. Second, local air quality issues governed by the Clean Air Act may well be impacted. For example, the initial fuels from synthetic paraffinic kerosene (SPK) are extremely low in sulfur content. This in turn lessens small particulate matter ($PM_{2.5}$), an increasingly regulated emission. The third dimension introduced by alternative fuel consideration is increased attention to changes in environmental life cycle, or "well-to-wing" factors. Alternative fuels may burn cleanly on the aircraft but add to overall emissions in their production and distribution processes.

These considerations include the need to capture and either utilize carbon dioxide (CO_2) via enhanced oil recovery or recycling, or store it permanently in the ground or in saline aquifers when such sources as nonrenewable coal or shale oil are used. Energy balance must also be considered along with land use, and water issues when biofuel crops are harvested. Lastly, the management of byproducts of the fuels themselves can mitigate the need for energy to be used directly to produce those products. In the case of CO_2 control, the added implications of such issues as the new Renewable Fuel Standard (RFS2) Environmental Protection Agency (EPA) measure and the related accounting for Renewable Index Number (or RIN) as a sustainability variable came into play in the 2009–2010 time period. While aviation does not have quotas for renewable fuel under RFS2, the calculation of RIN for aviation fuels will take place and can have implications for producers and users in ways that will evolve with time.

From a safety and operations perspective, aviation fuel, whether Jet A for commercial operations or its nearly identical military variant, JP8, differs from other transportation fuels in its strict requirements for safe operation over broad ranges of temperature and pressure. For these reasons, jet aviation must exclude the use of many current fuels used for ground transportation, such as ethanol. The use of other fuels that vary significantly in volume and density from current aviation fuels operating under American Society for Testing and Materials (ASTM) approved specifications (D-1655) would dramatically alter aircraft payload range characteristics for existing aircraft or require radical new aircraft designs and infrastructure at airports. The costs to make this transition for aviation could far exceed equipment and infrastructure costs associated with other transportation modes.

Given the limitations in specific energy required to accommodate current jet aircraft, for the foreseeable future, practical alternative fuels for aviation are limited to liquids that can be used with minimal to no modification of today's infrastructure, known as meeting "drop-in" requirements. Most commonly discussed of these are the following:

- Nonrenewable and renewable SPK fuels. These may take the form of natural gas-to-liquid (GTL), coal-to-liquid (CTL), biomass-to-liquid (BTL), or any combination of the above, frequently called XTL.
- Hydrotreated Renewable Jet (HRJ) from a variety of sources ranging from current feedstocks, such as Jatropha, to algae in the longer term. This category could also include animal fat residues in the mid-term.
- Sustainable aviation biofuel from alternative processes such as fermentation and pyrolysis (in the mid- to far-term).

Fuels that depart widely from ASTM D-1655 and ASTM D-7566 (for other alternatives to petroleum base fuels) density-volume norms (non-drop-in fuels) do not presently have a path to qualification or practical applications in current aircraft designs. Hence fuels of this type (such as hydrogen) are not addressed in this chapter.

Resource availability owing to the challenges of infrastructure development will ultimately govern which of the candidates are commercialized and the sites at which developments can take place. Prime in these considerations will be the match in scale between fuel production and the relatively concentrated nature of aviation fueling stations compared to other modes of transportation. For example, economies of scale for Fischer Tropsch (FT) CTL are achieved when production approaches 30,000 barrels per day. Sources of data on BTL production based on a variety of agricultural crops suggest that plant size may optimize at one-tenth that size.

Those considerations are significant when the fuel will need to be supplied to a centralized location such as Chicago O’Hare International Airport, where consumption may range from 5 to 100 times the supply available from any given plant. In the case of renewable fuels, the continuing availability and shelf-life of the feedstock also are critical.

Last, as a consumer of less than 10% of the transportation fuel used in the United States, aviation is hard-pressed to be a first mover in the quest for alternative fuels for transportation in the eyes of energy suppliers. The combination of issues described above requires that aviation interests hone the definition of their alternative fuel needs, develop the data needed to make the pursuit of aviation alternative fuels low risk (both technically and economically for potential suppliers), and agree and communicate clearly and concisely with the fuel supply chain their specific requirements.

The focus areas in which aviation needs to act fall into four fundamental disciplines:

- Research and Development (R&D): including initial demonstration of equipment compatibility to accepted risk management principles to achieve acceptable development and deployment risk.
- Certification and Qualification: to ensure the highest level of safe operation while preserving the mission of the vehicle.
- Environmental: to include both the measurement of outputs and the creation of life-cycle modeling tools for both greenhouse gases and current local air quality constraints for which the United States has developed state implementation plans under the Clean Air Act and National Ambient Air Quality Standards for $PM_{2.5}$.
- Business and Economics: to include issues associated with production of fuels that in some cases require additional production processes (hydrogenation of certain biofuels, for example), and distribution that may be unique to aviation’s airport-based fueling systems. These

issues include both high nonrecurring costs in the case of FT systems and potentially noncompetitive recurring costs in the case of some biofuels, when compared to biodiesels that may command a pricing premium for high cetane rated fuels. With the deterioration of the financial climate in 2008-2009, business interests now heavily depend on the availability of support from generally risk-averse financial institutions in a manner that has not been the case for decades.

CURRENT STATE

The current state of research in each of the four areas in each of the disciplines above can be described for each of the three candidate fuel types as follows:

Research and Development

- Nonrenewable sources of SPK fuels have largely emerged from the R&D phase and are now certified (see Certification and Qualification below).
- With certification in hand, R&D on FT processes turns to the need to:
  - Secure nonrecurring cost reductions in large facilities from current levels of greater than $100,000 per barrel a day;
  - Achieve the ability to optimize facilities at smaller plant sizes driving down economies of scale; and
  - Improve and optimize the gasification technologies (e.g., plasma arc) technologies to enable the most efficient waste-to-energy facilities.
- The creation of hydrotreated renewable jet (HRJ—also called Bio SPK) or other fuels using similar processes with varying feedstocks is expected to move from the research phase to certification by the end of 2010 or early in 2011 (see Certification and Qualification below). These fuels can be characterized as being derived from lipids from seed crops such as soybeans, jatropha, camelina, or salicornia.
- Significant research is being conducted by the Defense Advanced Research Projects Agency (DARPA) on biofuel from algae oil sources in pursuit of the highest potential yield per acre for lipid crops—as much as 100 times that of soybeans. That work is the subject of a 2008 research solicitation by DARPA and ongoing efforts from two teams that is now in the second phase of that effort.
- Other pathways to jet fuel production are now in play as well and generally fit into three categories:
  - Fermentation Renewable Jet (FRJ): derives jet fuel from sugars or crops such as sweet sorghum. In the case of FRJ fuels, genetically modified bugs ingest fuel sugar or cellulosic feedstock and excrete molecules in the jet fuel hydrocarbon range. Advance biofuels research is progressing with this fuel type and has entered engine subcomponent testing. A flight program is scheduled in Brazil with Embraer and GE in 2012 using this sugar feedstock grown in Brazil. In addition to private investments, DARPA also is investing in cellulosic FRJ research.
  - Pyrolisis Renewable Jet (PRJ): this fuel type extracts oil from cellulosic material. Such processing technology has been investigated by the U.S. Department of Energy (DOE). If successful, pyrolysis in smaller size facilities in comparison to current FT

plants could eliminate or reduce the need to transport large amounts of biomass to remote facilities. DOE has focused this research to date.

– Catalytic Renewable Jet (CRJ): covers a large range of technologies that can be similar to FRJ (without biological "bugs"), or can be revolutionary creating hydrocarbons without utilizing renewable plant life.

These technologies are now graded for their progression through technology and production readiness by a new risk management process called Fuel Readiness Level (FRL). An FRL process was developed by the U.S. Air Force (USAF) and members of the CAAFI R&D team and was accepted by the International Civil Aviation Organization as a global best practice during its November 2009 conference.

Certification and Qualification

A critical threshold was passed during 2005 with the adoption of protocols detailing generally accepted procedures for the approval of alternative aviation fuels by original equipment manufacturers of engines. These methods attack the most time-consuming core technical tasks involved in approving fuels and promise to radically reduce both the cost and cycle time for qualifying (or in the military, certifying) these fuels. These protocols are now documented as ASTM 4054.

Coupled with the increased levels of military and civilian investment in R&D, significant results have been achieved and continue to emerge:

- In September 2009, ASTM D-7566 was issued to enable 50/50 generic approval of a full spectrum of nonrenewable (e.g., coal and gas) to renewable (e.g., cellulosic biomass and animal fats) fuels. Initial passage also included an annex for the first of these new fuels from FT processes. The landmark ASTM D-7566 represented the first significant new fuel certification action in more than 20 years.
- The second round of fuel certification under ASTM D-7566 is to cover fuels categorized as HRJ or Bio SPK. A required research report for fuels in this category was completed in the first quarter of 2010. Dependent upon member response to the report and any needed action in response, committee approval is possible by the end of 2010, with publication in early 2011.
- Considering their technical status and future tests that remain, certification action for both blends of FRJ, PRJ, or CRJ likely under new annexes of and/or certification of 100% HRJ or FT fuels could come as early as 2013 if advanced fuels research progresses according to plans included in current CAAFI R&D roadmaps.
- To ensure work on feedstock availability occurs in parallel with fuel acceptance, an additional risk management communication process labeled Feedstock Readiness or FeRL has been established. FeRL is being discussed with both the U.S. Departments of Agriculture and Energy.

Environmental

Environmental efforts are concentrated on both particle measurement and building models to assess life-cycle costs for a full range of fuel types. However, the use of these tools to assess system capacity under the range of NextGen traffic projections has yet to be implemented using this information.

Measurements for $PM_{2.5}$ criteria pollutants were originally achieved on a T-56 engine type. Subsequent assessments of outcomes from B-52 aircraft testing of 50/50 GTL fuel and 100% CTL fuels on an engine rig were presented at the CAAFI annual meeting in 2007. Those measurements have been broadly disseminated. Emissions measurements of biofuel candidates to the standards set by the FAA Office of Environment and Energy began in the fall of 2007. Additional measurements occurred on a NASA test bed in 2008. Results have been reported and published as research under the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence. The conclusion that candidate SPK fuels have significant reductions in sulfur and $PM_{2.5}$ is an outcome of the initial testing. Some additional particle measurements also have been executed by European sources for incorporation into the database.

To date, particle measurement has been slowed by a lack of consensus on measurement standards by the governing Society of Automotive Engineers (SAE) committee. It is expected that SAE will agree on a standard by the end of 2010 and the accumulation of data will be able to keep pace with the myriad of new fuels being made available. Such data, once available, can be inserted in a number of models being worked in parallel with the measurement capability.

Three ACRP projects have been initiated that will contribute to a better understanding of commercial aviation alternative fuel use at airports. These include ACRP Project 02-07, *Handbook for Analyzing the Costs and Benefits of Alternative Turbine Engine Fuels at Airports* (*4*)*;* ACRP Project 02-18, *Guidelines for Integrating Alternative Jet Fuel into the Airport Setting* (*5*); and ACRP Project 02-23, *Alternative Fuels as a Means to Reduce PM2.5 Emissions at Airports* (*6*).

PARTNER has completed an initial well-to-wake life-cycle assessment of greenhouse gases of numerous alternative fuel candidates. Results released in May of 2010 adapt emissions predictions in the production processes from Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. GREET models specifically adapted to jet fuel affect accuracy in current studies.

Outcomes from PARTNER activity recognize that depending on means of execution and land use considerations, technology maturity for advanced feedstocks, such as algae, can vary widely. The PARTNER efforts recognize this by bracketing outcomes by uncertainty bands.

PARTNER calculation methodologies have been integrated with and embraced by efforts of a multigovernment agency coalition of DOE, Air Force, FAA, and EPA personnel as they have sought to demonstrate compliance with the mandates of Section 526 of the 2007 DOE authorization, which limits alternative fuel purchases to fuels that are better than an oil refinery on a life-cycle basis.

The peer reviewed methodology framework for life-cycle analysis (LCA) was issued in the fourth quarter of 2009 by the industry–government group that produced it. The framework was further accepted by the International Civil Aviation Organization as a best practice during its November 2009 conference in Rio de Janeiro.

Prospective fuel producers must conduct LCA according to both government and airline industry protocols, and monitoring and audit procedures also will need to be adopted to ensure that the submittals are to standard. Consideration of product category rules that currently are recognized by ISO 14000 are the leading candidates for that purpose.

Aviation is not subject to renewable fuel quotas under RFS2, however advantaged fuels can benefit their supply chain by producing positive RINs. The availability of RIN value could be an important incentive to spur alternative fuels deployment (see Business and Economics below).

Business and Economics

During 2009 and 2010, business and economics consideration took several important turns and are transforming the landscape for fuels deployment prospects:

- The development of formal memoranda of understanding (MOU) and execution of programs to deploy fuels globally, including
  - An MOU by eight airlines to purchase biomass-to-liquid green diesel for use at Los Angeles International Airport in September 2009.
  - An MOU by 15 airlines for two projects to negotiate terms for offtake agreements in Mississippi and Washington State in December 2009.
  - An MOU between British Airways, London City Airport, and a municipal solid waste-to-energy supplier in London, England.
  - The initiation of airline service using GTL-derived fuel in Qatar.
- In the United States, we see the beginnings of joint relationships between agriculture regions and aviation buyers to approach project developments on a full supply chain basis, the so-called "farm to fly" considerations. Proposed projects were submitted for USDA section 9000 and state projects in the north central United States.
- The recognition by DOE and the U. S. Department of Agriculture (USDA) that aviation can and should be considered a first mover in alternative fuels deployment. Specifically, policy direction included in a USDA/DOE interagency working group indicated "preestablished market outlets…with a concerted effort directed to our military and airline industry."
- Adoption by CAAFI of a definitive goal for some 10 success model projects by 2013. In addition to the three U.S. locations identified above, additional projects were under varying levels of consideration in five added states as of this writing.
- Policy targets established by both NextGen and the International Air Transport Association of carbon neutral growth by 2020.
- The formation of coordinated buyer alliances between airlines, and in March 2010, between airline and U.S. Department of Defense (DOD) buyers (Defense Energy Support Center).
- The emergence of nearly 50 companies seeking access to the alternative aviation jet fuel marketplace. Links to many of these companies are listed on the CAAFI website at www.caafi.org.
- Recognition of CAAFI from energy publications including *Biofuels Digest* as its Company of the Year.

Prior to 2009, studies of alternative fuel economics focused on the economics of introducing alternative fuels at airports as described above, and assessments of the overall economics of fuel production. Predictions of how much fuel could be available in the near term from various sources and what the costs of these options are in dollars per barrel equivalent crude are available from several sources, two of which are definitive and generally available. Other publications provide an inventory of plant construction. Specifically available resources of significant value to researchers include the following:

- Plans for the construction of both FT nonrenewable and combined CTL–BTL plants are published on a regular basis by DOE. Approximately 14 plants are on the drawing board in the United States. Ten times that number of plants are planned to be constructed outside the United States.
- The economics of CTL plants have been researched and well documented in studies by Scully Financial under contract to DOE, the U.S. Air Force, and EPA. Viable production pricing of $55 to $60 dollars a barrel was projected in the 2006 to 2007 time period, including carbon capture (but not sequestration) for plants of 30,000 barrels per day or larger. More recent studies have been executed by both Noblis and DOE's National Energy Technology Lab for biofuel-coal to liquid plants. Prices are higher in the later studies commensurate with increases in commodity costs for plant construction, feedstock costs for biomass in particular, and feedstock transportation costs. They remain, however, in price ranges encountered for oil-derived fuels in the same time period.
- A case study of a similarly sized plant situated in south central Illinois using a combination of coal and biomass feedstock was the subject of a study performed by Princeton University and presented to the PARTNER Carbon Sequestration Workshop. The study concludes that similar fuel costs are theoretically achievable with biomass contributions from switchgrass offering 20% of the total. When combining the life-cycle benefits of 20% biomass and employing carbon sequestration, the fuel production can have a carbon-neutral footprint. The cost of biomass to obtain carbon neutrality with an approach desirable to crop producers is on the order of $100 per ton.

While progress in 2009–2010 has been extremely encouraging, the lack of private sector financing for projects initiated with the financial crisis that began in 2008 has been and continues to be a drag on implementation. To address that issue, CAAFI and its sponsors have initiated evaluation of financing policies and launched communications with such agencies as the World Bank and the InterAmerican Development Bank in an effort to initiate projects globally.

There is also currently a better understanding of the potential for airports and their tenants to utilize nearby biofuel facilities off-airport and to act as a distribution hub for fuels to other transport modes using the airport, and conceivably for the distribution of coproducts from refineries.

FUTURE VISION

- Qualified alternative fuels available from the maximum number of feedstocks and processes that can produce drop-in fuels that should be fully interchangeable and indistinguishable in meeting airline operating requirements need to be approved to allow local sources of supply to prosper independently of feedstock choice.
- Carbon neutral growth for aviation should be achieved by 2020 with a 50% reduction in the aviations carbon footprint by 2050.
- Recognition of aviation as the global leader in sustainable, drop-in alternative fuel implementation.

- Production levels of alternative fuels should increase rapidly so that aviation fuels from domestic sources can supplement petroleum supply by some certain date to help ensure supply security.
- Assurance of competitive price and price stability: minimal price fluctuations owing to localized disruptions in supply should be enabled along with a return to historical levels of crack spreads for aviation fuels ($5 order of magnitude) and elimination of the need to tanker fuel (i.e., carrying more fuel on-board than is necessary for the flight and buying less higher-priced fuel along the route of flight) as a result of disruption.
- Airports and their airline tenants forming the basis for multimodal distribution of transportation fuels and coproducts from biofuel production facilities.

RESEARCH NEEDS

- Evaluate technology options to provide cost reductions to improve the attractiveness of investment to financial sources that demonstrates and proves reliable in production scale for all fuels.
- While environmental tools exist, they need to be widely applied and directed to the full range of potential production options. The existence of needed data to expedite timely certification is critical to success. In particular, the $PM_{2.5}$ data for the full range of alternatives needs to be made available and incorporated in the emerging tool set. R&D on all viable renewable processes ensures the attainment of certifiable fuel properties; thus pilot plant production capability to amounts in excess of 250,000 gallons will be required to allow tests in multiple combustor types, including rich burn, lean burn, and afterburner configurations for this purpose. Research funds should focus in particular on cellulosic and fermentation and other processes that offer the promise of significant supplies.
- In the case of BTL, key efforts are needed to demonstrate that gasification via co-fired or separate gasifiers can achieve high performance and reliability standards. Other technologies to reduce cost and improve durability are required.
- Technology demonstrations of full systems to optimize and broaden water usage (more saline, poorer quality) is required to ensure that energy facilities do not compete with water for food crops and human and livestock consumption.
- To ensure certification is achieved expeditiously for all fuels, issues that may exist in the use of any fuels related to their fitness for purpose should be identified and examined early through government sponsored research (USAF, FAA, and others) to ensure they are not the critical path in fuel approval.
- There are many unknowns relative to the long-term durability on any new process. Specifically, questions about the effects of seal swelling characteristics (reduced sulfur fuels) and altered lubricity characteristics suggest there is a need for evaluating extended durability on fuels that go into service. While not evident from the available data, durability issues could also affect airport fuel handling (filtration and storage), reflecting a need to extend research efforts on durability at the facility level.
- Research to eliminate uncertainties in pipeline distribution of biofuels, such as water hiding, needs to be undertaken. The aviation fuel supply will depend not only on production, but also on the economics of use.

- Evaluating the development and implementation of feedstock readiness criteria for alternate fuels. Participation of government agencies including USDA, FAA and DOD to ensure these technologies meet technology readiness Level 5 criteria (production scale-up), in particular, is critical.
- On the macro level, a scenario analysis considering optimized production scenarios for a matrix of Jet A, nonrenewable, and renewable fuels, coupled with the range of NextGen traffic forecasts and agreed-upon fuel usage growth, will both assist in the assessment of suppliers' ability to meet system needs and provide a realistic assessment of what is achievable in terms of aviation emissions.
- A toolkit to provide states and local investors with a means of assessing their ability to arrive at viable solutions combining any of the three production options with available resources would be an extremely valuable aid to streamlining implementation efforts.
- Explicit and rigorous quality control criteria need to be developed and implemented at the factory level as well as at the distributions centers on airports (to the extent needed) in addition to current practice to address any quality concerns.
- Research on how to optimize the economic and environmental benefits for such facilities over all modes that utilize the airport is needed to maximize the potential interest of fuel suppliers to locate production facilities at or near the airport.

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Sustainability

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One cannot open a newspaper, read an aviation industry publication, or hear a television or radio broadcast without the concept of "sustainability" being mentioned. Sustainability has captured the attention of both the public and the business world. Although the term has been used in Europe and other international markets for many years, it has only recently become a common term in the United States. Many people within the aviation industry have embraced it as a way of doing business and have made great progress, while others are still puzzled by what the term means, or they fear that it is the cloak of another antigrowth movement that will negatively impact their businesses. This disparate understanding and implementation is a critical issue that calls for increased education, information sharing, and research.

There are many definitions of sustainability, one of the most famous being the Brundtland Commission definition: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." These needs usually are grouped in three broad categories: economic, social, and environmental. Several metaphors are used to illustrate the need to balance and trade-off among these categories of needs. The "triple bottom line" often is used in the business context to show performance metrics, not only for the traditional financial bottom line, but also for environmental and social bottom lines. The "three-legged stool" metaphor shows that the three legs of economy, equity, and environment all must be equal to support the confluence of the three in the seat of the stool as sustainability. The "wedding cake" metaphor shows that a healthy economy depends on a healthy society, which in turn depends on a healthy environment. The common theme is that any one of these broad categories of needs cannot be ignored or exploited if the enterprise is to be successful for the long term. Ten years after the first sustainability plan was prepared for a U.S. airport, the definition of sustainability is still the subject of debate.

CRITICAL ISSUES

For the aviation industry, the term sustainability immediately raises several questions:

- What is the main driver for sustainability: climate change, environmental impact, social or economic necessity, or the cost of fuel?
- What is to be sustained: the global economy, the aviation industry, an airport, the environment, or the community?

- What areas are we considering: the airports, the entire trip from take-off to landing, or the market area that an airport serves?
- Who takes responsibility for sustainability actions: airports, air carriers, customers, or regulators?
- How can sustainability be measured: is there a national or international standard that airports should be striving to achieve?

The tools and methods of managing the sustainability of complex systems are beginning to be developed and applied to aviation:

- Transparency is a broad set of communication tools to make the various and complex trade-offs increasingly visible to the stakeholders of sustainability strategies.
- Life-Cycle Analysis is a methodology for evaluating the benefits and costs of a project for the entire time of its useful life, taking upfront planning and construction costs into account, balanced against operational and environmental or other costs for the useful life of a project or facility.
- Scenario Planning is a method for forecasting a variety of possible long-range futures and developing plans for an enterprise that are resilient in adapting to a variety of possible scenarios.
- Asset Management systems keep track of an organization's entire portfolio of assets and their relative risk and value to the system.
- Systems Dynamics Models are computer simulation programs that can evaluate very complex system interdependencies in multiple future scenarios. Developing effective applications of each of these tools for aviation is a critical research need.

The policy challenges raised by sustainability for aviation are critical. There are the challenges of the aircraft manufacturers as they deal with engine emission controls and the development of alternative fuels. The airlines share in that challenge but also face the issue of serving the public while struggling to make a profit with their existing fleets of aircraft. There are different challenges for airports, including economic development, noise, air, and water pollution, and traffic congestion. Airport tenants, concessionaires, cargo handlers, and the traveling public have other sets of challenges. There is a critical need for effective policy and technical analysis on all of these topics.

The impact of aviation on climate will be a critical driver in the discussion of sustainability. While there has been great progress during the last 5 years in the development and certification of alternative jet fuels, development of alternative aviation fuel on a commercial scale is still in progress. In contrast to aviation, other modes of transportation have more alternatives available given the fewer operational restraints of ground-based transportation. Climate change drives two important parts of aviation sustainability: reducing the greenhouse gases emitted by air transportation (often called mitigation), and dealing with the environmental changes being caused by global warming, such as sea level rise and higher temperatures (often called adaptation). There are many basic and applied research needs in these topic areas, ranging from developing and using alternative propulsion technologies to changing the way the overall aviation system is managed and the role of aviation in meeting society's needs. These topics have a large influence on the sustainability of aviation, affecting both the ability of airplanes to fly and the ability of certain airports to remain physically viable, due to factors such as inundation from sea level rise.

Extensive climate change research has already started, as referenced in other sections of this chapter. Topics such as alternative aviation fuels with a lower life-cycle (greenhouse gas) GHG profile, the global warming effects of high-altitude GHG emissions, alternative modes of airport access, and electrification of airport ground service vehicles address this critical national and global concern. Additional research is needed on the following topics to improve climate change programs and their contributions to sustainability:

- What role does aviation play in the sustainability of metropolitan regions and countries?
- What path can aviation take to phase out the use of fossil fuels?
- What criteria can be used to assess performance in pursuit of sustainability?
- What shared tools will help the aviation industry advance its sustainability?
- What is an effective framework for making trade-offs among, and valuing, the triple bottom lines?
- Can aviation be conducted in a way that protects the environment, does not adversely impact communities around airports, and still be profitable?
- What strategies can help aviation organizations and users to rapidly adapt to increasing stakeholder pressures regarding sustainability, from local to global?
- How can climate change mitigation and adaptation considerations be incorporated into airport master planning, airline fleet planning, and air traffic control system planning?
- How will organizational expenditures (operations and capital construction) be balanced with mitigation and adaptation programs?
- What strategy needs to be undertaken to keep up with evolving climate change research and policy while maintaining consistent performance standards and meeting public expectations (this is sometimes called “changing the tires while driving down the road at 60 mph”)?
- How will the aviation industry find better methods of engaging and aligning stakeholders to achieve better decisions and higher program efficiency?
- What approach is needed to create altogether new and more flexible methods for making shared decisions about critical trade-offs between valued resources, such as wildlife, plant life, water, minerals, disease vectors, sound levels, and so forth?
- Who will create shared information utilities to manage the systems data associated with many of the above topics, to reduce the organizational costs of sustainability programs?

CURRENT STATE

Many organizations in the aviation industry are addressing the issue of sustainability and are devising their own metrics and reporting systems. Best practices include the use of sustainable design standards such as the U.S. Green Building Council’s Leadership in Environment and Energy Design certification program for built facilities; the Global Reporting Initiative (GRI) that disseminates globally applicable sustainability reporting guidelines for voluntary use by organizations reporting on their economic, social, and environmental conditions; and International Organization for Standardization (ISO) 14001:2004, which establishes the requirements for environmental management systems (EMSs), confirming a global standard for organizations wishing to operate in an environmentally sustainable manner. In addition, ISO 26000, released in 2010, will provide additional guidance for social responsibility frameworks and metrics.

In response to federal, state, or local mandates for implementing sustainable practices, airport managers are forming green teams to develop strategies for reducing the net impact of operations. Organizations are conducting air emission inventories of traditional criteria pollutants, as well as diesel emissions and GHG emissions, and then developing programs to reduce emissions. Water conservation programs are getting increased attention as drought plagues many parts of the world. The Sustainable Aviation Guidance Alliance (SAGA), a broad volunteer coalition of aviation interests formed in 2008 to assist airport operators of all sizes in planning, implementing, and maintaining a sustainability program, has undertaken an effort to consolidate existing guidelines and practices into a comprehensive, searchable resource that can be tailored to the unique requirements of individual airports of all sizes and in different climates and regions in the United States. Some of these programs and best practices are shared at www.sustainableaviation.org. In 2011, the TRB Airport Cooperative Research Program (ACRP) will manage an update to the SAGA database. EMSs are being used to set goals, institutionalize best practices, and track environmental information and performance. In some cases, those EMSs are evolving into sustainability management systems to track triple-bottom-line performance. FAA is embarking on a pilot program to fund sustainable master plans and stand-alone sustainability plans with the goal of developing FAA’s policy toward incorporating sustainability in the airport planning process.

Despite efforts by many aviation industry interest groups, there is not yet a single, accepted aviation sustainability standard that benchmarks progress and provides a comparable basis for measurement of success. In the spring of 2010, draft legislation was before the US Senate to develop consensus-based best practices and metrics for the sustainable design, construction, planning, maintenance, and operation of airports; a consensus-based rating system for airports based on best practices and metrics; and a voluntary rating process for airports. In the place of this legislation, the industry has looked to ACRP for research on sustainability for airports, including best practices, success metrics, and potentially a certification program specifically for airports. There are many options to be considered in every decision that is made. There is no common metric or measure to determine if any segment of the industry is becoming more sustainable. Several U.S. and international airports are following the GRI process to set standards for airport sustainability performance. However, it is still challenging to compare activities or airports or businesses because of their unique characteristics. This is not limited to the aviation industry.

Moreover, most entities in the United States continue to focus disproportionately on the environmental aspects of sustainability, while continuing to employ financial metrics that are very traditional and short-term as opposed to life-cycle and long-term. Social and community aspects are generally considered separately, without attempts to integrate them into basic decision making, and programs dealing with the social aspects of employee relations are also considered separately, despite research that shows employee recruitment and retention are tied to a business’ reputation as it pertains to sustainability. Although there has been much written on the concept of sustainability, specific applications to the aviation industry have been lacking.

Through all of this, growth in aviation markets throughout the world is mixed. Due to the economic downturn, passenger traffic on International Civil Aviation Organization member airlines declined 3.1% overall in 2009 and in the U.S. there were sharp declines averaging close to 7%; in 2009, Asian air traffic grew and eclipsed North America as the world's largest aviation market. However, all longer-term forecasts are for continued growth and airports continue to plan for expansion. For example, by 2013, Asian traffic is projected to grow and have a market share of about one-third of the world market. Yet, growth and expansion are being challenged on new grounds, including climate change. For example, a proposed expansion at London's Heathrow airport was stalled by a judge requiring additional analysis of the project's climate implications.

FUTURE VISION

The vision for the future is that there would be a common understanding of the concept of aviation industry sustainability among businesses, governmental entities, and the public. Aviation industry sustainability will incorporate growth and expansion to serve the public demand worldwide for air travel. Standardized life-cycle cost analysis tools will be readily available for all aspects of the aviation industry and will be widely used. There will be an accepted system or standard for measuring sustainability efforts within the aviation industry that promotes creativity and recognizes differences among participants. There will be mechanisms for both self-reporting and independent third-party verification of the application of the standard to an entity. There will be a global reporting system for the aviation industry that takes data from local entities and consolidates them into national and global data structures. The effects of climate change will be taken into account when planning for future projects.

Research will continue on all environmental fronts for solutions with less impact on, and possibly improvement to, the environment. Research will continue on community and social implications of decisions, and it will factor equally with environmental and fiscal considerations.

RESEARCH NEEDS

- Research regarding integrated intermodal transportation systems to maximize fuel and energy efficiency and consideration of overall environmental, social, and economic impacts.
- Research on implications of a transeconomy—the intersection of a strong economy (or economic recovery) and a strong transportation infrastructure of which aviation is a part.
- Development of aviation industry standards for sustainability, including common metrics for comparison within and among organizations.
- Research regarding the relative role and contribution of aviation access to the economic, social, and environmental development of both the various regions of the United States (including urban and rural) and developed and developing countries.
- Research on success stories where growth occurred while incorporating the triple bottom line and corresponding lessons learned where growth was stymied.
- Synthesis of sustainability practices by airport operators, airports, airlines, airport tenants, and concessionaires.
- Synthesis of U.S. federal, state, and local regulations, mandates, and executive orders that require airports to adopt sustainable practices.

- Enhancing SAGA's ability to compile tools currently being used to implement sustainable solutions.
- Sharing of best practices and research worldwide.
- Development of automated collaboration methods for collecting, updating, tracking, and visualizing system performance data.
- Research on effective life-cycle cost analysis tools, and how to best apply life-cycle cost analysis to the aviation industry and businesses within it.
- Development of information technology to allow mining of data for life-cycle cost product information.
- Development of technical information regarding sustainable environmental solutions.
- Research on the requirements for climate change adaptation and new standards for long-term aviation infrastructure development.
- Methods for incorporating ISO 26000 social responsibility frameworks into sustainability programs.

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Environmental Review Process

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Conducting environmental review under both the National Environmental Policy Act (NEPA) and similar state-based reviews at airports can result in a complex, controversial, and often inefficient process. Airport operators are finding that their internal processes for project planning and development often are not well integrated with the NEPA process requirements FAA must complete, requiring revisions to analyses. Protracted environmental documentation can impede development, increase costs, and further polarize the relationship of the airport operator with regulatory agencies and airport neighbors. Some of the public believe that the NEPA process fails to address important objectives in terms of resource protection and preservation of quality of life. Further, a segment of the public believes that the NEPA process does not necessarily lead to better project decisions and, instead, may simply confirm a choice that had already been made.

The form and implementation of environmental review, management, and compliance processes are important for determining whether critical stakeholder needs are met. A complex set of laws and policies guides airport development, airspace changes, compliance with environmental requirements, and development of aviation technology and products. Airport development is guided by, among other things, FAA's orders and advisory circulars. The environmental review process itself is guided by NEPA and Council on Environmental Quality Regulations, as well as by special purpose laws, such as the Clean Water Act, the Clean Air Act, etc. and FAA Orders, such as 1050.1E and 5050.4B and their revisions. In addition to the federal requirements, there are a variety of state and local laws that may include NEPA-like processes, as well as state-level special purpose laws.

Environmental review, management, compliance, rulemaking, and enforcement roles are shared among entities at the federal, state, and local levels, for example: airport owners; the federal FAA, Environmental Protection Agency, Army Corps of Engineers, and Fish and Wildlife Service; state environmental agencies; airport tenants; and municipalities. These activities often are undertaken in ways that do not always ensure complete coordination, which can increase the time, cost, and difficulty of project approval and compliance with environmental requirements, but that may or may not advance the goals established for the process. Public opposition and litigation on environmental grounds also add time and increase the uncertainty of the environmental review processes.

Environmental issues associated with aviation are pivotal to the future development of aviation infrastructure. Environmental concerns are primary factors slowing the development of additional airport capacity in many areas. Both the perception and the reality of noise, air pollution, incompatible land development, water quality, traffic congestion, and other environmental effects—as well as the level of trust or confidence in analyses of these effects and the ability to mitigate them—drive political, legal, and other decisions that affect the ability to expand the aviation system in a timely manner. Similarly, decisions regarding aviation have real effects on the environment that may or may not be fully consistent with federal, state, and local environmental assessments preceding the decisions. Increasingly, airports, airlines, and manufacturers also are looking at proactive environmental management or sustainability management approaches to meet business or policy objectives beyond strict compliance. An improved understanding of the strengths and weaknesses of the environmental review, management, and compliance processes associated with aviation is critical.

CURRENT STATE

In the fall of 2000 and in subsequent policy statements, the aviation industry and Congress gave increased attention to additional capacity at congested airports. Many stakeholders identified environmental processes (the analyses conducted under NEPA) among the causes for delays in implementing capacity initiatives. Government and industry entities increased efforts to evaluate how well current environmental processes work within the aviation context and to identify means of better meeting the goals of environmental requirements. These efforts included the U.S. Department of Transportation (DOT) report to Congress in 2001, *Environmental Review of Airport Projects*, and the U.S. Government Accountability Office 2000 report, *Aviation and the Environment: Airport Operations and Future Growth Present Environmental Challenges*. Industry organizations such as Airports Council International–North America (ACI-NA) and the American Association of Airport Executives identified proposals to address perceived shortcomings of current processes. Environmental organizations and local governments also have expressed concerns with the manner in which aviation environmental issues are addressed.

FAA has implemented streamlining initiatives identified in the DOT report to Congress. In 2002, the President issued Executive Order 12374 to promote environmental stewardship and expedited environmental reviews of high-priority transportation infrastructure projects, including airport infrastructure. Congress included provisions intended to streamline environmental review for aviation projects in Vision 100, the FAA reauthorization bill for 2004–2007. In 2003, a task force appointed by the President's Council on Environmental Quality (CEQ) issued a report identifying ideas for possible reform of federal environmental reviews. CEQ is implementing some of these ideas and considering others. In June 2004, FAA issued an updated version of its agencywide guidance on environmental policies and procedures (Order 1050.1E–*Environmental Impacts: Policies and Procedures*). In April 2006, the agency issued an update to the *Airport Environmental Handbook* (FAA Order 5050.4B), retitled as *National Environmental Policy Act (NEPA) Implementing Instructions for Airports*. Order 5050.44B was followed in October 2007 with the *Environmental Desk Reference for Airports,* which is intended to provide more detailed and updated guidance regarding environmental review requirements outside NEPA (e.g., the Clean Air Act, Section 106 of the National Historic Preservation Act, etc.).

In February 2010, the CEQ issued new draft guidance regarding how mitigation measures should be developed, implemented, and monitored in the NEPA process. The guidance reflects CEQ's intent to require more aggressive implementation of mitigation measures. "[As] identified in several studies, ongoing agency implementation and monitoring of mitigation measures is limited and in need of improvement." *Draft Guidance on Mitigation and Monitoring under the National Environmental Policy Act* (Feb. 2010) has the potential to change significantly how environmental reviews are conducted, creating more emphasis on the enforcement of mitigation measures after the completion of the traditional environmental review process. This may start to blur the lines between environmental review and environmental management.

There also has been an increase in attention to improvements in environmental management. In April 2000, the President issued Executive Order 13148, *Greening the Government Through Leadership in Environmental Management*, which required federal agencies to adopt principles and approaches associated with environmental management systems (EMSs). To promote airport EMSs, FAA will finance the development of EMSs at large and medium hub airports.

An EMS is intended to methodically assure environmental goals and requirements are brought into organizational decision making from top to bottom and to continuously manage environmental issues through a cycle of planning, implementation, data collection, and review for changes—a process known as "Plan, Do, Check, Act." FAA and other stakeholders currently are working to make the EMS a guiding concept for the Next Generation Air Transportation System. In addition, other aviation entities have been using EMSs or related concepts to manage environmental issues. For example, a number of airports have secured International Organization for Standardization 14001 certification for all or part of their facilities, and other major airports have developed comprehensive EMSs.

Despite these initiatives, a considerable gap in knowledge regarding aviation-related environmental review and compliance processes remains. There has been relatively little study conducted by neutral parties to determine objectively and empirically the effectiveness of these processes and the causes of the sometimes lengthy time periods to review and approve airport projects. In meetings of ACI-NA and the Airport Consultants Council, airport and environmental planners have noted that one of the reasons the NEPA process can take longer than expected is that timing of project and physical planning is not always well integrated with NEPA processing needs. In 2009, *ACRP Synthesis Report 17: Approaches to Integrating Airport Development and Federal Environmental Review Processes* identified contributors to prolonged NEPA processes, instances where the project development process and NEPA were not well integrated. Simultaneously, a group of volunteers from ACI-NA has formed a Planning–NEPA integration task force. This group is collaborating to develop a best management practice document to identify lessons learned and recommend actions and issues that should be considered to better integrate project planning and environmental review processes.

Finally, without further analyses, it is unclear whether any of the initiatives that have been undertaken in the past few years relating to environmental review have made significant and lasting improvements in practice. A better understanding of the actual effects of recent initiatives and problems associated with integrating project development and environmental reviews will be important in developing new and more efficient decision making.

FUTURE VISION

Improving the processes for conducting environmental reviews, ensuring environmental compliance, and improving the management of environmental issues at airports will require

- Improved analytic tools;
- Improved environmental management systems;
- Improved processes to integrate planning and environmental reviews;
- Improved ways to ensure sufficient planning and other needed data are available for the follow-on environmental analyses;

- Using sustainability initiatives and measures to reduce a project's environmental effects and provide or enhance its social and economic benefits;
- Incentives for and new methods to ensure timely interagency cooperation,;
- Elimination of procedural requirements that slow and complicate processing without producing clear benefits in terms of decision making;
- Consideration of alternatives to traditional forms of regulation; and
- The use of communication technologies to enhance the transparency and public understanding of a proposed project, its alternatives, and their environmental effects.

RESEARCH NEEDS

Research is needed to support improvements in environmental review, management, and compliance processes to better achieve timely development of aviation services and environmental protection. Environmental review, management, and compliance processes should, among other things:

1. Inform decision makers and the public of the environmental impacts of projects;
2. Support selection and implementation of projects that promote transportation and sustainability (i.e., environmental, social, and economic) goals;
3. Ensure compliance with environmental requirements;
4. Ensure transparency and accountability within and outside an organization for environmental requirements or goals;
5. Work within reasonable and predictable timeframes; and
6. Minimize costs.

Objective and empirical research regarding the effectiveness, efficiency, accuracy, and shortcomings of environmental processes applicable to aviation, as well as potential means to improve these processes, would be useful to policy makers in evaluating whether existing processes should be changed and, if needed, in what manner. Many of these research needs arise in the context of the environmental review of new aviation projects, while others relate primarily to ongoing management of and compliance with environmental requirements.

Identifying ways the FAA, sponsors, and consultants can better integrate project planning with the needs of the environmental review process is a key objective. Both the environmental review and compliance contexts are important to the protection of the environment and the health of the aviation industry. Specific research needs involving the aviation environmental process should consider

- Evaluating the adequacy of current environmental review and management tools for addressing new environmental challenges, such as climate change;
- Identifying the time environmental review and compliance processes currently require for various airport projects and determine why such timelines vary by project type, regional location, and impacts;
- Developing guidance for document preparers to improve their efficiency and document quality, providing a library of approved NEPA document sections that describe analyses, and provide discussions of airport-related environmental effects;

- Identifying the probable causes of time delays in decision making, including
  - Disputes about purpose and need,
  - Disputes about alternatives,
  - Multiagency coordination issues,
  - Why environmental problems can be difficult to solve,
  - Issues related to developing mutually acceptable mitigation, and
  - Efficiently addressing community opposition and highly controversial issues.
- Identifying why and how project revisions occur;
- Identifying if processes lacked staffing or other resources;
- Locating critical bottlenecks in the review process and developing possible solutions that would still meet process and substantive goals;
- Assessing the effects of current and forthcoming streamlining and other process measures, as well as the effects of implementing new regulations or guidance to make the review process more efficient;
- Assessing the effectiveness of environmental documents in clearly disclosing impacts, risk, and complex topics, such as noise, air pollution, air toxics, capacity, and forecasts;
- Developing approaches for conveying aviation-related environmental information in brief, understandable, and meaningful ways;
- Considering the potential relationships between environmental management or sustainability management systems and traditional environmental review processes;
- Determining the best ways of developing and integrating forecasts into the environmental review process;
- Evaluating the use of mitigation monitoring, how that contributes to adaptive management, and the use of that information to determine the effectiveness of the monitored mitigation for use in future airport projects;
- Considering the effectiveness of sustainable practices and programs, including environmental effects, costs and benefits, and relationships with affected communities;
- Reviewing the adequacy of mitigation tools available to address community concerns and opposition, as well as the effects of mitigation on the decision-making process (an effort that links with the research needs listed in the noise, air quality, water quality, and tools sections).
- Analyzing the factors critical to addressing community opposition and concerns;
- Assessing the effectiveness of environmental and sustainability management tools, as well as alternatives to the command and control compliance model in the aviation context;
- Studying the effects and adequacy of legal processes affecting aviation environmental planning, such as land use and metropolitan transportation planning processes, occupational safety litigation, and takings and nuisance litigation; and
- Evaluating the effectiveness of components of the environmental review process and developing measures to benchmark best practices.

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The Next Generation of Aviation Environmental Modeling Tool Suite

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The adverse environmental by-products of aviation affect civil aviation's capacity to grow and to operate. Although there are multiple by-products and interdependences that are important to understand, mitigating noise and emissions as well as fuel burn (which directly impacts climate), are particularly critical and more directly relevant to aircraft and engines. Delivering technologically and economically feasible decreases in noise, emissions, and fuel burn is a growing challenge. Substantial progress already has been made, particularly in reducing jet engine noise and fuel burn. However, passenger and cargo aircraft and gas turbine engines are maturing technologies, and the growing complexity of aircraft systems compels an interdisciplinary approach to aircraft design to achieve future advances. Moreover, progress in noise and emissions mitigation should employ a mix of source reduction technologies with operational procedures, controls, and land use management, in the case of aircraft noise. The challenge is to understand the interdependencies between aircraft noise and aviation emissions and among emissions of various air pollutants to optimize mitigation strategies and to minimize environmental impacts as a whole. It is equally critical to employ robust cost–benefit environmental analyses to inform decision-making processes. Performing interdependent analyses of aircraft noise, emissions, and fuel burn, as well as translating these environmental effects into monetized impacts pushes the limits of computer modeling capabilities today. That is why exploiting continuously increasing computing power will play an important role in achieving that understanding.

The advancement of superior support tools will enable an interdisciplinary approach to assessing aviation environmental impacts and interrelationships. These tools should give decision makers—including the aviation industry, government, and the public—the information they need to develop responsive strategies: cost-effective strategies driven by benefits that allow aviation to grow in an environmentally responsible manner. The aviation industry needs to analyze the interdependencies among noise and emissions in both the design and operating contexts. Government agencies need to assess the consequences of proposed regulatory environmental actions and policy decisions in terms of the effects on noise, climate change and air pollutant exposure, as well as the economic consequences. The public needs reliable and clear information on noise and emissions impacts to participate effectively in decision making that could affect public health and welfare. Assessing impacts and interrelationships is a complex issue, and it will take time to develop interdisciplinary decision support tools. Meanwhile, it is important to also maintain a state-of-the-art analytical capability to support ongoing needs for aviation noise and emissions analyses.

Future environmentally responsible aviation policy and rulemaking needs to be based on a new, interdisciplinary approach. This approach should be made as affordable as it is effective and informative. Integrated modeling tools are needed to effectively assess and communicate environmental effects, trade-offs, interrelationships, and economic consequences. Accordingly, the Federal Aviation Administration (FAA), in collaboration with the National Aeronautics and Space Administration (NASA) and Transport Canada, is 6 years into a multiyear effort to develop a robust new comprehensive framework of aviation environmental analytical tools and methodologies that will enable more informed federal policy and budgetary decision making and facilitate international agreements on standards, recommendation practices, and mitigation options. The long-term aim is to provide a seamless, comprehensive set of tools to address all aspects of aircraft noise and emissions.

CURRENT STATE

The FAA has been at the forefront of developing and deploying models to evaluate aircraft noise and aviation air pollutant emissions around airports, notably the Integrated Noise Model (INM) for singular airport analyses, the Noise Integrated Routing System (NIRS) for regional noise assessment, and the Emissions and Dispersion Modeling System (EDMS) for both singular and regional airport emissions capabilities. FAA also has developed the Model for Assessing Global Exposure to Noise from Transport Aircraft (MAGENTA) for national and global noise assessments, and the System for Assessing Aviation's Global Emissions (SAGE), to estimate aircraft fuel burn and emissions over the entire international and domestic flight regime. NASA is at the forefront of developing aircraft and engine design and analyses models that also encompass predictive capabilities for noise and emissions. These models include aircraft noise prediction, advanced vehicle performance analysis, and engine performance and mechanical design tools.

Efforts to address aircraft noise and aviation air pollutant emissions issues historically have advanced largely along independent paths, with separate foci, modeling tools, research projects, analyses, metrics, and decisions. As a result, the current legacy analytical tools are inadequate to assess interdependencies between noise and emissions or to analyze the cost and benefit of proposed actions.

Over the past few years, the FAA Office of Environment and Energy, in collaboration with Transport Canada and NASA, has focused on developing a comprehensive tool suite that allows aviation noise, emissions, and fuel burn inventories and thorough assessment of the environmental impacts of aviation. This tool suite comprises the Environmental Design Space (EDS), Aviation Environmental Design Tool (AEDT), Aviation Environmental Portfolio Management Tool for Economics (APMT-Economics) and Aviation Environmental Portfolio Management Tool for Impacts (APMT-Impacts). Once fully mature, this integrated tool suite will be capable of characterizing and quantifying the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs and associated environmental benefits under different policy, technology, operational, and market scenarios.

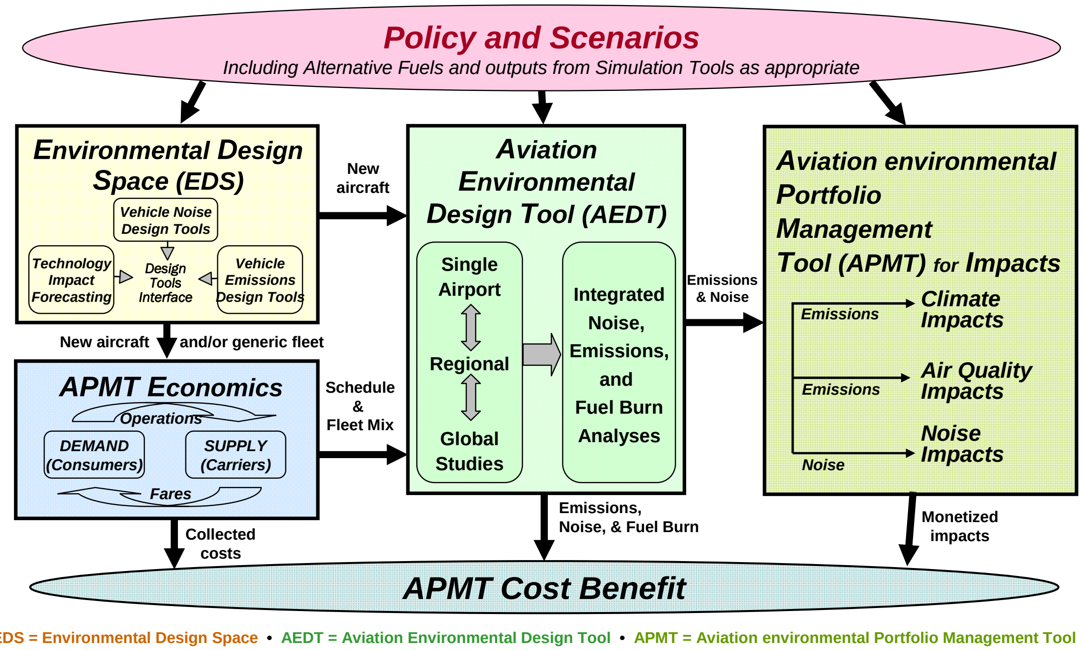

FIGURE 1 Schematic of the Aviation Environmental Tools Suite.

Figure 1 shows a simplified schematic of the new tool suite. EDS estimates source noise, exhaust emissions, and performance for potential future and existing aircraft designs. AEDT takes detailed fleet descriptions and flight schedules as input and models aircraft performance in 4-dimensional space and time to produce fuel burn, emissions and noise at global, regional, and local levels. AEDT development integrates FAA's current environmental tools: INM, NIRS, EDMS, MAGENTA, and SAGE. The APMT-Economics tool models airline and aviation market responses to environmental policy options. The APMT-Impacts tool takes the outputs from AEDT and estimates the environmental impacts of aircraft operations through changes in health and welfare endpoints for climate, air quality and noise. These environmental impacts are quantified using a broad range of metrics including, but not limited to, monetized estimates of human health and welfare impacts, thereby enabling both cost-effectiveness and cost–benefit analyses.

While the legacy basis of these tools is at various stages of development, each area of the tool suite is currently functional for global and national policy analyses. Tool suite development and the capabilities of its various components have been presented and discussed at four FAA-sponsored Transportation Research Board workshops. Domestic and international aviation sector stakeholders actively participated in these workshops and provided constructive feedback on the development of the tool suite.

A key element of the ongoing tool suite development is the assessment and evaluation relative to fidelity requirements and sensitivities to input assumptions. This assessment is designed to identify possible gaps in functionality of the tool suite as well as identify the individual modeling input parameters that contribute to the largest uncertainty in the model output. In essence, the model assessment activities provide a research road map for future tool investments and improvements. To meet these objectives, there are four different elements to the assessment program: (1) parametric sensitivity and uncertainty analyses; (2) comparisons to gold standard data (a benchmark that is regarded as the most reliable, representative, or complete information available); (3) expert reviews; and (4) capability demonstrations and sample problems. These assessments are being done on both an individual model and full suite system level.

FUTURE VISION

When completed, the new Aviation Environmental Tools Suite will allow government agencies to understand how proposed regulatory actions and policy decisions impact aviation noise and emissions; allow industry to understand how technology, design, and operational decisions related to proposed airport and airspace projects affect aviation noise and emissions; and allow the public to understand how actions by government and industry impact community noise and emissions. In coordination with the Next Generation Air Transportation System Joint Development and Policy Office, the tool suite currently is being used for environmental-related scenarios and policy analyses.

RESEARCH NEEDS

An interdisciplinary approach to noise and emissions modeling builds on continued improvement of individual noise and emissions modules. Related tasks include developing, integrating, and validating databases and methods used to assess aircraft noise exposure and impacts, aviation pollutant emissions and impacts on air quality, and global aviation emissions and impacts on climate. Specific research needs involving aviation environmental tools include the following:

- For EDS, combine existing NASA acoustics and performance modules with engine emissions models into an integrated package for evaluating inter-relationships between noise and emissions at the aircraft level, taking into account aircraft cost considerations, performance capabilities, and operational factors. We must create the software architecture, design module links, and harmonize database architecture such that a seamless interaction between the tools exists under different technology and policy scenarios.
- For APMT-Impacts, integrate research advances for new environmental impact metrics, and socio-economic data.
- For EDS, AEDT and APMT, advances are needed to fully integrate the various elements of each model, as well as create a user interface and input and output protocols.
- Advance the quantitative assessment of the tool suite at the system level and continue uncertainty analysis to provide guidance on the level of confidence that we can place on tool outputs and encourage international acceptance.

FAA is pursuing development of the Aviation Environmental Tools Suite models with their intended uses ranging from design and technology impact studies, to airport improvement projects, to noise and emissions certification standards rulemaking, to incremental human health impacts from the aviation sector.

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Technology Deployment

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Research into the fundamental effects of aviation on the environment of the type described in the previous sections of this paper cannot be converted into improvements that would reduce those effects unless the recommended technologies are actually developed and deployed in the field. The pace and scope of deploying new technologies within the aviation enterprise in an increasingly complex future depends on numerous factors, many of which are not well understood. These factors include the following:

- **How to introduce new technologies within the existing aviation system interface constraints:** Demonstrating the efficacy of new technology to meet its intended environmental goal is necessary but not sufficient to ensure its deployment in aviation. New technology intended to address environmental performance must meet the same high reliability, durability, maintainability, and increasingly significant security standards applied to other components of the aircraft. These requirements can be a barrier to deployment by disqualifying some technologies entirely, mitigating the net environmental gain, or producing high economic penalties.
- **How to make new technologies marketable:** Manufacturers outside aviation or conglomerates may not perceive aviation to be a sufficiently large market or have a viable business model to support development of products tailored to this sector. For example, there is minimal fuel cell or micro turbine research concentrating on potential airport applications, although it could be used in many pieces of airport equipment.
- **How to determine costs and benefits of new technologies:** The economic costs and benefits to end users of technology that has an environmental benefit to communities are not well understood, and there is no widely accepted metric by which to measure them.
- **How to develop optimal trade-offs:** The interrelationship of aircraft components may force suboptimization of one technical characteristic to avoid sacrificing others. For example, innovations in engine technology resulted in quieter, more fuel-efficient aircraft but increased emissions of nitrogen oxides.
- **How to stimulate commercial risk-taking:** Government research programs in the United States are not developing new technology to a level that would allow private enterprise to adopt it at reasonable risk. In the past, the National Aeronautics and Space Administration (NASA) sponsored technology to the system demonstration level known as Technology Readiness Level 6 (TRL6). For example, during the 1980s, NASA sponsored both engine and aircraft full-scale demonstrations under its aircraft energy efficiency program that were taken to TRL6, which produced significant innovation in commercial products in the ensuing years. No such programs exist today.
- **How to approach risk-averse financial institutions:** Only one U.S. airline (Southwest) has a bond rating above BBB; as a result, they are viewed as a poor credit risk by the financial sector.

- **How to meet future demands:** By 2025, the volume of traffic in the National Airspace System (NAS) will significantly increase. However, current business processes and information technology systems are not designed to accommodate such volume. The Joint Planning and Development Office (JPDO) has undertaken the Next Generation Air Transportation System (NextGen) project to modernize and transform the NAS to accommodate future growth in aviation. The JPDO Environmental Working Group is working within the NextGen process to minimize the risk that environmental concerns will constrain future growth and transformation of the NAS. Such efforts include development of advanced technologies and development of tools to assess environmental impacts and inform policy decisions and advancement of scientific research (particularly on climate impacts). At the same time that technology innovation has flagged, the national needs for dramatic improvements in reducing aviation's impacts on the environment have become more obvious. The JPDO is incorporating an environmental plan to ensure there is no growth in environmental exposure in the United States as this capacity growth occurs, but such a plan depends on deployment of advanced technology. Those impacts have acquired dimensions beyond local air quality in the control volume around airports. It now incorporates a very significant greenhouse gas concern that extends well beyond the airport boundaries.
- **How to address future issues:** Emerging issues, particularly those that are not governed by aviation-specific regulatory bodies at the time of their emergence—such as particulate matter, hazardous air pollutants, and deicing—require thorough aviation-specific research before optimum solutions can be identified, and often even longer time periods before appropriate technologies can be designed, produced, and introduced into the market. Without such definition well in advance of control requirements being defined, timely development and deployment of solutions is not possible.

CURRENT STATE

Aviation is a mature industry, and the pace of innovation has decreased as the industry has matured. Technological advances over the past 50 years have resulted in aircraft and engines that are increasingly quieter, more fuel efficient, and produce fewer pollutants. During the last decades of the 20th century, new commercial aviation systems were deployed at a rapid pace, filling voids in aircraft size and range and frequently following on the heels of military aircraft developments in similar size and speed classes. At this time, the feasible range of speed and size for commercial aircraft has been explored and few voids exist. Most of the current technological innovation takes the form of improvements to existing aircraft types, and the economic barrier to replacing an existing product in the same size and speed class is high.

Research is being conducted that begins to address critical deployment issues. For example, the issue of optimal technology trade-offs in aircraft design was first evaluated by a consortium of airline operators and manufacturers in support of international regulatory investigations earlier this decade. It is being addressed further under the FAA's Environmental Design Space initiative. The shortfall in environmental capacity resulting from the planned threefold increase in aviation activity is being evaluated by the JPDO environmental team.

Additional mechanisms are also becoming available to approach analysis of problem statements and subsequent means to quantify the value of deployment by quantifying the ability of new technology to achieve sustainability goals in ways that are quantifiable. Several have occurred in the arena of alternative fuels and are communicated in that related paper.

Aircraft and engine companies are using new technology that promises as much as a 10 dB improvement in cumulative noise and 10% to 15% reduction in fuel burn over the best current turbofans to differentiate their new products from established aircraft producers in the 100-seat market.

Low NO_X engine technology also continues to progress and must be maintained as noise and CO_2 progress is made. This is necessary if only to hold to the standards achieved for low NO_X as higher bypass engines typically optimize at greater combustor exit temperatures.

The FAA’s Continuous Lower Energy Emissions and Noise (CLEEN) Program awards announced in June 2010 represent yet another significant effort to further technology from early research toward certified products and processes. CLEEN is focused on the maturing and commercial transition of near-term technologies that significantly reduce aircraft noise, emissions, and fuel burn, as well as alternative fuels. Five industry partners have been selected and the technology development efforts include development of market transition strategies. CLEEN research efforts are expected to result in environmental technologies that will begin to be put on aircraft by 2015. Government investment of $125 million over 5 years is planned with the corresponding industry share to bring the total investment in green aircraft technologies to more than $250 million.

FUTURE VISION

Additional data, analysis, and tools to improve deployment of environmental technologies are needed to address the collective goals of all participants. That data and analysis should cover the full spectrum of issues affecting deployment, be usable by all interests, and enable informed decision making by creating the best possible understanding among and between the engaged enterprise components. In developing data analysis and tools, priority should be given to

- A complimentary domestic and international research approach to develop common tools for analysis, which will greatly improve technology deployment prospects.
- The quantification of sustainability variables (environmental, economic, and social) that provide metrics that link to business and regulatory analysis.
- Aviation’s continued emphasis on a globally-approved set of rules to address the unique nature of aviation issues.
- Aviation’s emphasis on using its strong systems capability, and global environmental approach to be considered a first mover in environmentally friendly technology among all transportation modes.

Means of communicating this information are needed as effectively as possible across the aviation enterprise and to those that interface with it. The generation of this information is envisioned to lead to a reduction in the barriers to technology deployment and thus allow reductions in the impact of aviation on the environment.

RESEARCH NEEDS

Specific research needs identified to best address the critical issues in technology deployment include the following:

- Conduct research on business processes to include identification and investigation of case studies from other transportation modes and similar technology-intensive industries. Determine how technology innovation has best occurred in other industries that depend on environmental performance and are in similar mature positions on the S-curve of industry life cycle. Such management science studies can produce lessons that are applicable to aviation as it migrates through its maturity phase.
- Incorporate multimodal analysis in technology evaluations. It is particularly important to articulate overall environmental performance of aviation technologies in comparison to other modes of transportation. By documenting environmental benefits of new aviation technologies, airports and aircraft operators can showcase the opportunities around which technology deployment should be stimulated.
- Develop an adequate benchmark of case studies of specific technologies that had to meet equally high standards as they have progressed from demonstration to implementation and insertion at a systems level. Such a set of studies can alert evaluators to the scope and magnitude of penalties that can be anticipated in the deployment of new aviation environmental technologies.
- Target research and review case studies to identify the transferability of environmental technologies first deployed in other industries to aviation. This in turn would establish aviation feasibility for systems shown to be reliable and safe and could enable users to create strategies that cross multiple markets. Conversely, while aviation may not be the largest market for some technologies, it may have characteristics (contained–controlled test space) that make it desirable for beta (user) testing of new products targeted for multiple markets. Offers by the aviation industry to house such tests could speed insertion into the general market. Research should be targeted to identify opportunities where this approach may be attractive.
- Research is needed to determine the costs and benefits of environmental improvements. While the acquisition and recurring cost consequences of new technologies are available to operators from manufacturers, the research need is for third party (neither seller nor buyer) monetization of benefits to operators if existing economic penalties are ameliorated through improved product performance. Here, amelioration can take the form of reduced fees, capacity constraints, purchase of environmental credits, and operational changes such as noise abatement flight tracks. For U.S. Department of Defense (DOD) operations, amelioration may take the form of reducing tanker requirements, training costs, or maintenance costs if the most effective basing cites are unavailable. This research recommendation follows the initiative to develop a balance sheet of costs and benefits, which was an outcome of the Aviation Environmental Portfolio Management Tool workshop conducted by the Transportation Research Board at the request of FAA during the first quarter of 2005.
- Continue research to determine optimal trades among environmental factors in aircraft design at least into the production flight test phase where product form, fit, and function are established.
- Research ways to reduce the risk of introducing new technology and stimulating commercial investment. For example, quantify, in an objective manner, the percent chance of

success and payoffs for key technologies and systems of multiple technologies. The DOD–NASA technology readiness process, which has existed since the 1990s, can be used as a model to collect data on projects at all risk levels. This includes but is not limited to the implementation of Fuel Readiness Level (FRL) process developed by the Commercial Aviation Alternative Fuels Initiative (see Aviation Alternative Fuels Development and Deployment chapter) and a feedstock readiness process (FeRL in the case of alternative fuels for aircraft).

- Research that quantifies the benefits and costs of developing and deploying advanced technology to meet NextGen capacity requirements to the satisfaction of all enterprise components needs to be executed in a timely manner. By identifying enterprise pull (motivated by potential growth), this research could define a national objective basis for market-based deployment.
- Research means of establishing mechanisms to detect at the earliest possible occasion new environmental requirements that could impact aviation technological development.
- Identify and evaluate where government action (other than research) has accelerated identification and deployment of technology in aviation and in other industries both inside and outside the United States. Careful selection of these examples to ensure that they have similar key characteristics as aviation will be critical to this initiative's success. Better understanding of how such tools can be used most effectively would enable the U.S. government to speed deployment of aviation technologies that would benefit the environment.
- Added research to ensure introductory financial incentives are adequate for the successful deployment of new technologies. These incentives must maximize investments in not only the aviation sector, but also in industries that can serve the industry and enhance its first mover status.

RESOURCE

Environmental Integrated Product Team. *Technology Pathways—Assessing the Integrated Plan for Next Generation Air Transportation System*. ISBN 0-309-65283-PDF, Appendix G, Draft Plan, 2005.

Readers are encouraged to request additional references from the author.

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