For Greener Skies: Reducing Environmental Impacts of Aviation

DETAILS

70 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-08337-9 | DOI 10.17226/10353

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FOR Greener Skies

Reducing Environmental Impacts of Aviation

Committee on Aeronautics Research and Technology for Environmental Compatibility

Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

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This study was supported by the National Aeronautics and Space Administration under Contract No. NASW 99037. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number: 0-309-08337-0

Available in limited supply from: Aeronautics and Space Engineering Board, HA-292, 2101 Constitution Avenue, N.W., Washington, DC 20418, (202) 334-2855.

Additional copies available for sale from: National Academy Press, 2101 Constitution Avenue, N.W., Lockbox 285, Washington, DC 20055, (800)-624-6242 or (202) 334-3313 (in the Washington metropolitan area), http://www.nap.edu

Cover artwork by Nila Rusnell Oakes. *Stratus Composition,* 1999, oil on canvas, 48″ × 48″.
Internet: http://www.nilaoakes.com

Printed in the United States of America

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Preface

Each new generation of commercial aircraft produces less noise and fewer emissions per passenger-kilometer (or ton-kilometer of cargo) than the previous generation. However, the demand for air transportation services grows so quickly that *total* aircraft noise and emissions continue to increase. Meanwhile, federal, state, and local noise and air quality standards in the United States and overseas have become more stringent. It is becoming more difficult to reconcile public demand for inexpensive, easily accessible air transportation services with concurrent desires to reduce noise, improve local air quality, and protect the global environment against climate change and depletion of stratospheric ozone. This situation calls for federal leadership and strong action from industry and government.

U.S. government, industry, and universities conduct research and develop technology that could help reduce aircraft noise and emissions—but only if the results are used to improve operational systems or standards. For example, the (now terminated) Advanced Subsonic Technology Program of the National Aeronautics and Space Administration (NASA) generally brought new technology only to the point where a system, subsystem model, or prototype was demonstrated or could be validated in a relevant environment. Completing the maturation process—by fielding affordable, proven, commercially available systems for installation on new or modified aircraft—was left to industry and generally took place only if industry had an economic or regulatory incentive to make the necessary investment. In response to this situation, the Federal Aviation Administration, NASA, and the Environmental Protection Agency, asked the Aeronautics and Space Engineering Board of the National Research Council to recommend research strategies and approaches that would further efforts to mitigate the environmental effects (i.e., noise and emissions) of aviation.

The statement of task required the Committee on Aeronautics Research and Technology for Environmental Compatibility to assess whether existing research policies and programs are likely to foster the technological improvements needed to ensure that environmental constraints do not become a significant barrier to growth of the aviation sector. This assessment was required to answer the following questions:

- What lessons can be learned from previous U.S. research investments in environmental controls for the aviation sector?
- Where are the most attractive opportunities for research and technology investments to ensure that expected growth in the aviation sector will be consistent with environmental protection goals?
- What approach should the U.S. government use and how should it interact with the private sector and other research establishments (in the United States and overseas) to carry out governmental responsibilities for investing in technology for mitigating the environmental effects of aircraft noise and emissions?

The goal of this assessment was to recommend a framework for government research policies and programs aimed at achieving technological change fast enough for commercial aviation to grow in an environmentally sustainable manner. The recommended approach should be consistent with agency roles and missions as defined in existing legislation. The focus of the study was on commercial aviation and did not include intermodal issues, such as how the air transportation system could be modified in concert with other elements of the total transportation system to reduce the overall environmental impact of transportation.

The tragic attacks of September 11, 2001, on the World Trade Center and the Pentagon had a serious and immediate impact on the U.S. air transportation system. The long-term implications remain to be seen. This study is based on the expectation that the reduction in air travel following the attacks is a temporary perturbation of the historic trend of increasing demand for air travel. Thus, the current period of reduced air travel does not solve the environmental challenges associated with aviation, although it may provide additional time to address those challenges.

John A. Dutton, *Chair*
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Technology for Environmental Compatibility

Acknowledgment of Reviewers

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

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

Acknowledgment of Participants and Contributors

The committee appreciates the assistance of the following individuals, who provided information to the committee at its information-gathering meetings.

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Executive Summary

Providing rapid and safe transportation across the nation and around the world, contemporary aviation contributes significantly to the national economic vitality and to the business and pleasure of millions of citizens. In addition, the manufacture of aviation products provides substantial direct economic benefits as a source of jobs in the United States, and as the largest positive contributor to the balance of trade in goods. But large amounts of energy are required to propel modern jet transports, and thus both noise and emission of combustion products are a consequence of powered flight.

Scientific and technological progress in the 50 years since the advent of turbine engines has produced dramatic reductions in their noise and emissions. But even though individual airplanes are quieter and cleaner, the rapidly increasing demand for aviation services has mandated more airplanes and more flights, and so the total environmental consequences have increased and become more obvious. At the same time, the awareness of environmental issues and the political pressures to resolve them have also increased dramatically. Aircraft operations and the construction of new facilities are now seriously constrained by environmental restrictions. Indeed, the U.S. air transportation system is caught today between two powerful but conflicting expectations—the first for more services, the second for decreased environmental impact. The presumably short-term reduction in demand for air travel in the aftermath of the September 2001 attacks on the World Trade Center and the Pentagon does not resolve the issues addressed by this report. It merely provides an opportunity for advanced technology to mitigate existing environmental impacts before the inevitable resumption of demand growth makes them worse.

The technical challenges are too large and regulatory and economic incentives too small for industry acting alone to eliminate the environmental effects of the growth in air travel and the demand for aviation services. The federal government has long accepted part of the responsibility for the advance of aviation and for reducing its environmental impact. But today the federal research efforts are not commensurate with the intensifying severity of the problem. While the goals of the federal research program are admirable and focused on the right issues, the schedule for achieving the goals is unrealistic in view of shrinking research budgets and increasing isolation from industry and academia. As research budgets are cut, a higher percentage of the remaining funds are spent to support in-house work at National Aeronautics and Space Administration (NASA) research centers. This causes an even larger reduction in the percentage of research funding left for research and technology development by universities and industry.

Most of the federal funding available for addressing issues associated with aircraft noise and emissions is used for noise abatement at selected airports, primarily by soundproofing buildings in high-noise areas outside airport boundaries or purchasing land to extend airport boundaries to encompass high-noise areas. Relatively little is spent on research and technology to control noise or emissions at the source. This funding scheme is a consequence of the way funds are raised and appropriated. Most of the funds appropriated for these purposes are raised from taxes on airline tickets, primarily for the purpose of subsidizing airport improvements or noise abatement measures in homes and other buildings near airports, and they are administered by the Federal Aviation Administration (FAA). Primary responsibilities for developing advanced aircraft technologies for reducing noise at the source, however, are assigned to NASA, which has no independent sources of funding to support aeronautics research.

Finding—Vigorous Action Required. Environmental concerns will increasingly limit the growth of air transportation in the 21st century unless vigorous action is taken to augment current research and technology related to the environmental impacts of aviation.

AIRCRAFT NOISE

Aviation noise reduces property values, contributes to delays in expanding airport facilities, and prompts operational restrictions on existing runways that increase congestion, leading to travel delays, high ticket prices, and high airline capital and operating costs. The situation would be much worse, however, if not for past investments in advanced technology. Over the past 30 years, the number of people in the United States affected by noise (i.e., the number of people who experience a day-night average sound level of 55 dB) has been reduced by a factor of 15, and the number of people affected by noise has been reduced by a factor of 100, as measured per unit of service provided (revenue-passenger-kilometer).

The most significant limitations to further reductions in the effect of aviation noise (or emissions) include growth in demand, long lead times for technology development and adoption, long lifetimes of aircraft in the fleet, high development and capital costs in aerospace, high residual value of the existing fleet, and low levels of research and development funding. While spending huge sums on local palliatives such as soundproofing buildings, the federal government reduced funding for the research that would quiet the entire fleet in the decades ahead. For example, the noise reduction element of NASA's Advanced Subsonic Technology Program was an excellent model for government-industry collaborations involved in commercialization of advanced technology. This program has been terminated, however, and replaced with a new program with fewer resources and less industry involvement.

In 2001, the FAA expended about $500 million on noise abatement, while the FAA and NASA together expended less than $60 million on noise and emissions research. The need to place more emphasis on research was noted in the fiscal year 2002 appropriations for the Department of Transportation, which directed that $20 million from the Airport and Airway Trust Fund be used to accelerate the introduction of quieter aircraft technologies. These funds were provided to the FAA, with the expectation that it would "work directly with" NASA "to advance aircraft engine noise research," and about $14 million is being used to augment NASA research funding in this area. Congress took this action because community opposition to aircraft noise is preventing the necessary expansion of some airports and because "aircraft noise results in millions of federal dollars being spent each year on mitigation measures, diverting funds which could be applied to capacity enhancement or safety projects" (Congress, 2001). The committee endorses this action as a first step in reducing the imbalance in the allocation of aircraft noise funding. Much more needs to be done.

Most federal research on noise reduction is performed or managed by NASA. NASA's goals for noise reduction are to cut the perceived noise of future subsonic aircraft in half (i.e., by 10 dB) between 1997 and 2007 and to cut the noise in half again by 2022 (NASA, 2002). Achieving these goals will be very difficult—and will require a rate of technological advance that is greater than the historical record would predict (see Figure ES-1). Furthermore, even in the unlikely event that these aggressive goals are achieved, noise may continue to constrain the U.S. air transportation system, in large part because communities near airports are placing greater emphasis on a low-noise environment as part of their quality of life.

The Federal Interagency Committee for Aircraft Noise facilitates information sharing among federal agencies interested in aircraft noise. This committee could be strengthened and made more effective if agencies appointed personnel who have budgetary authority within their home organizations as members of the committee.

Recommendation—Balanced Allocation of Funds. Federal expenditures to reduce noise should be reallocated to shift some funds from local abatement, which provides near-term relief for affected communities, to research and technology that will ultimately reduce the total noise produced by aviation. Currently, much more funding is devoted to local abatement than to research and technology. Also, to avoid raising unrealistic expectations, the federal government should realign research goals with funding allocations either by relaxing the goals or, preferably, by reallocating some noise abatement funds to research and technology.

Recommendation—Technology Maturity and Scope. NASA and other agencies should sustain the most attractive noise reduction research to a technology readiness level high enough (i.e., technology readiness level 6, as defined by NASA) to reduce the technical risk and make it worthwhile for industry to complete development and deploy new technologies in commercial products, even if this occurs at the expense of stopping other research at lower technology readiness levels. NASA and the FAA, in collaboration with other stakeholders (e.g., manufacturers, airlines, airport authorities, local governments, and nongovernmental organizations), should also support research to accomplish the following:

- Establish more clearly the connection between noise and capacity constraints.
- Develop clear metrics for assessing the effectiveness of NASA and FAA noise-modeling efforts.
- Implement a strategic plan for improving noise models based upon the metrics.
- Harmonize U.S. noise reduction research with similar European research.

Recommendation—Interagency Coordination. Interagency coordination on aircraft noise research should be enhanced by ensuring that the members of the Federal Interagency Committee for Aircraft Noise have budget authority

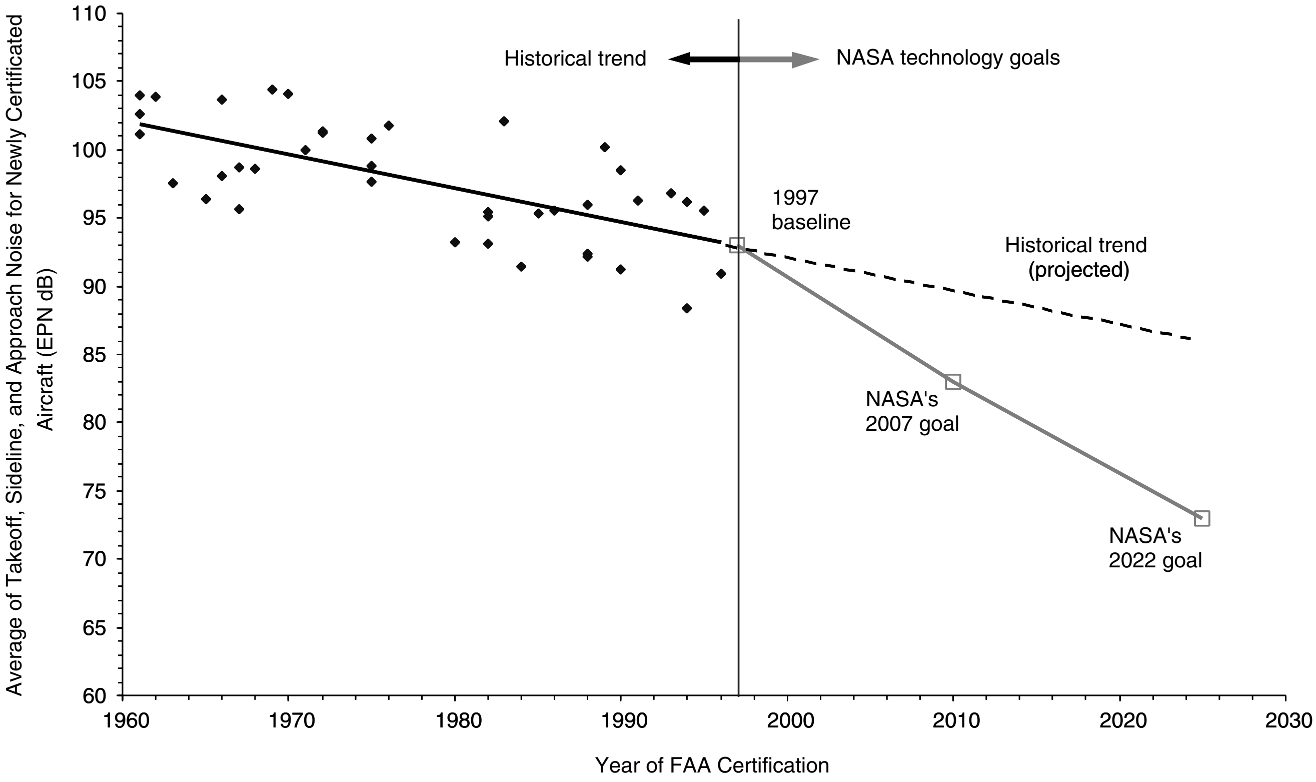

FIGURE ES-1 Historical trends in aircraft noise compared with NASA's noise goals. SOURCE: Lukachko and Waitz, 2001.

within their own organizations to implement a coordinated strategy for reducing aviation noise.

ENGINE EMISSIONS

The aviation industry is growing, and the use of aviation fuel is increasing at a rate comparable to that for other uses of fossil fuels. Between 1992 and 1999, the United States increased its consumption of natural gas (10 percent), petroleum (12 percent), and coal (13 percent). The consumption of jet petroleum increased by 14 percent, and the consumption of petroleum products by the entire transportation industry increased by 15 percent. Jet petroleum represents 3 percent of the total U.S. energy consumption and some 10 percent of petroleum consumption.

All other factors being equal, the amount of emissions produced by aircraft is essentially proportional to fuel consumption, which is proportional to flight activity. One option for reducing emissions is advanced technology, and during the past 50 years major advances in aircraft turbine engines have been realized as a result of extensive efforts by engine manufacturers and cognizant government agencies. In the United States, NASA has been a significant contributor to these sustained advances. From the outset, the goals of these efforts have included improved engine reliability, durability, and fuel efficiency, all of which have significant economic implications for the airlines. Dramatic progress has been made in all three of these crucial aspects, but the increased efficiencies of individual airplanes are not sufficient to decrease the total emissions of a global fleet growing in response to accelerating demand. For newly designed aircraft, advanced technology could reduce fuel consumption per revenue-passenger-kilometer by about 1 percent per year for the next 15 to 20 years. During the same time, however, the demand for global air transportation services is expected to increase by 3 to 5 percent per year (see Figure ES-2).[1] An aggressive, broad-based research program that includes technology to improve propulsion systems, the airframe, and operational systems and procedures could significantly close this gap, but existing allocations of research funds within NASA and the FAA are insufficient to support such a program.

Funding allocated to achieve NASA's goals for reducing carbon dioxide (CO_2) and oxides of nitrogen (NO_x) is insufficient to reach the specified milestones on time. Research to reduce NO_x and improve engine efficiency, although part of the NASA Ultra Efficient Engine Technology Program, has been significantly reduced in scope in the past few years to

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[1] The September 11, 2001, attacks on New York City and Washington, D.C., will shift plots of future growth in air travel to later years. However, lacking data on how much of an adjustment to make, the committee is relying on historical projections which reflect trends that are expected to resume in the long term.

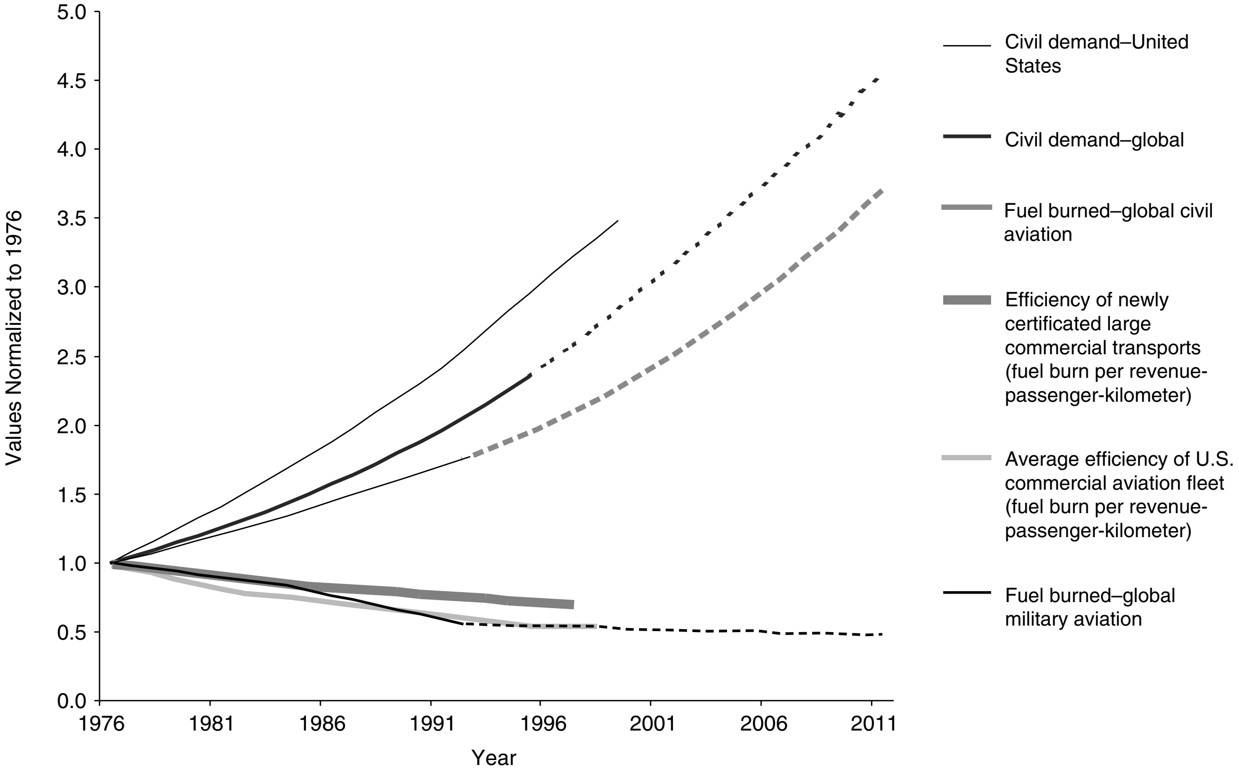

FIGURE ES-2 Decadal trends for demand, efficiency, and fuel usage. Dashed portions of curves are projections. SOURCE: Lukachko and Waitz, 2001.

accommodate NASA's shrinking aeronautics research budget. These reductions jeopardize achievement of program goals and do not appear to carry the research far enough so that results can be readily adopted by industry.

Additional scientific research is also needed to set appropriate regulatory standards and to frame technology development goals and plans. Research is needed to (1) clarify the extent to which aircraft effluents introduce hazardous air pollutants into the airport environment; (2) examine the formation of particulates and aerosols in aircraft engines and exhaust plumes during idle, taxi, and flight; and (3) quantify the effects of aircraft emissions on radiative forcing in the atmosphere, the formation and persistence of cirrus clouds, and climate change globally and regionally. Even though large uncertainties remain regarding aviation's effects on the atmosphere, research budgets for examining this issue have been cut by two-thirds in recent years.

Recommendation—Eliminating Uncertainties. NASA should support additional research on the environmental effects of aviation to ensure that technology goals are appropriate and to validate that regulatory standards will effectively limit potential environmental and public health effects of aircraft emissions, while eliminating uncertainties that could lead to unnecessarily strict regulations.

Recommendation—Research on Global, Regional, and Local Emissions. NASA should continue to take the lead in supporting federal research to investigate the relationships among aircraft emissions (CO_2, water vapor, NO_x, SO_x, aerosols, particulates, unburned hydrocarbons, and other hazardous air pollutants) in the stratosphere, troposphere, and near the ground, and the resulting changes in cirrus clouds, ozone, climate, and air quality (globally, regionally, and locally, as appropriate). Other agencies interested in aircraft or the environment should also support basic research related to these programmatic goals.

ENVIRONMENTAL COSTS AND BENEFITS

The conflict between the increased demand for aviation services and more stringent environmental constraints mandates a careful examination of the associated economic and political realities and policies. The government has responsibilities for fostering aviation as a contributor to the national infrastructure, for defining realistic environmental goals, and for developing environmental policies and regulations to meet such goals. To ensure that the goals and policies are appropriate, the full extent of environmental costs, the economic benefits of reducing noise and emissions, and the potential of financial incentives for owners and operators to reduce environmental impacts should all be considered.

Manufacturers attempt to produce new aircraft that cost less and are more reliable than their predecessors. At the same time, government intervention is important to encourage manufacturers, operators, and consumers of aviation services to reduce the environmental consequences of aircraft operations, which will sometimes increase costs. There are international implications, too, because many domestic rules are written in accordance with multinational agreements established by the International Civil Aviation Organization; also, other nations sometimes unilaterally establish rules that affect the operations and competitiveness of U.S. aircraft or airlines.

Thus, the government is an active participant in promoting aviation and in ensuring the environmental compatibility of aviation, both by assisting in the development of new technologies and in regulating the noise and emissions that attend aircraft operations. An important question is whether the current policy framework is well equipped to satisfy both environmental goals and the public's demand for aviation services. One way to consider this question is to examine the full costs for consumers, operators, and manufacturers of doing business in competitive markets, including the costs related to environmental compatibility and the consequences of inadequate facilities and capacity. Knowing the full costs of operations, the likely costs and consequences of technological intervention, and the costs of the potential solutions (technological and regulatory) would allow policy alternatives to be ranked and better policy decisions to be made.

An associated policy issue is whether it is possible to create marketplace incentives for industry to develop and deploy environmental technologies that go beyond regulatory requirements. For example, a few major European airports have implemented landing fees that reward operators who use ultralow-NO_x combustors while penalizing operators using standard combustors. The cost differential does not appear to be a sufficient financial incentive to most international air carriers, for whom operations at these airports represent a very small fraction of their total operations. As a result, advanced combustors, some of which can reduce NO_x as much as 60 percent below international standards, have a limited market because (1) they cost more than simpler combustors (that reduce NO_x to about 35 percent below current standards) and (2) they provide no economic benefits to offset their higher cost.

Recommendation—Considering All Costs and Benefits. To support the formulation of environmental goals and air transportation policies, government and industry should invest in comprehensive interdisciplinary studies that quantify the marginal costs of environmental protection policies, the full economic benefits of providing transportation services while reducing the costs (in terms of noise, emissions, and congestion), and the potential of financial incentives to encourage the development and use of equipment that goes beyond regulatory standards.

A CALL FOR VIGOROUS FEDERAL LEADERSHIP

Strong action is essential to avert a paralyzing collision between the growth of aviation and increasing concerns about the quality of the environment. A national strategy and a federal plan for action are much needed. Two significant issues must be faced:

1. *Technology lead times.* With service lives of 25 to 40 years for individual models of commercial aircraft, it can take decades for a major technological improvement to appear in a majority of the commercial fleet. NASA, the FAA, and industry could reduce lead times by collaborating in the development of mature, proven technology that the FAA is willing to certify, airlines are willing to purchase, and manufacturers are willing to develop.
2. *Economic incentives.* The government and the public must recognize the need for economic incentives for manufacturers and airlines to embrace technologies that minimize environmental impacts. Although passengers are unlikely to pay more to ride on an airplane with lower takeoff or approach noise, they may be willing to pay more to fly in a newer airplane that offers other advantages in addition to reduced environmental impacts. More certain, however, is the ability of the government to establish economic incentives for using advanced environmental technologies. Possibilities include tax advantages for operators of "greener" airplanes and direct grants for environmental innovation or leadership.

Finding—Status of Environmental Research. Research seeking to mitigate the environmental impacts of aviation is important to national and global well-being, but present efforts are operating with ambitious goals, unrealistic timetables for meeting them, and few and diminishing resources.

The ultimate goals for environmental research related to aviation remain uncertain for several reasons:

- The actual effects of aviation on the environment are uncertain.
- Aircraft emissions are only a small contributor to global atmospheric issues.
- Solutions may involve revolutionary changes in aircraft design.
- The noise levels that will ultimately prove acceptable to the general public (especially to people living near airports) and eliminate noise as a critical limitation on the growth of air traffic are unknown.

Recommendation—Additional Research. To reduce conflicts between the growth of aviation and environmental stewardship, NASA, the FAA, and the Environmental Protection Agency (EPA) should augment existing research by developing specific programs aimed at the following topics:

- determining which substances identified by the EPA as hazardous air pollutants are contained in aircraft emissions and need to be further reduced
- understanding and predicting atmospheric response to aircraft emissions as a function of time on local, regional, and global spatial scales
- exploring the suitability of alternate sources of energy for application to aviation, taking full account of safety and operational constraints

Recommendation—Taking Advantage of Experience. The following lessons, learned since the advent of jet-powered aircraft, should be used to formulate and evaluate strategies for reducing the environmental effects of aviation:

- Success is not easy—it requires government support and federal leadership in research and development of new technology. Establishing a strong partnership involving federal, state, industry, and university programs is essential to progress.
- Changes in the impact of aviation on the environment occur on the scale of decades as fleets evolve; technological success in reducing adverse impacts occurs on the same or longer scales.
- The formulation of technological strategies to reduce the environmental impacts of aviation is hampered by significant uncertainties about (1) long-term effects of aviation on the atmosphere, (2) economic factors associated with aircraft noise and emissions, and (3) the level of noise and emissions that ultimately will prove to be acceptable to airport communities and the general public, nationally and internationally.

With a final recommendation, the Committee on Aeronautics Research and Technology for Environmental Compatibility calls for leadership by the federal government to ensure the growth of an environmentally compatible national aviation capability in the 21st century:

Recommendation—The Federal Responsibility. The U.S. government should carry out its responsibilities for mitigating the environmental effects of aircraft noise and emissions with a balanced approach that includes interagency cooperation and investing in research and technology development in close collaboration with the private sector and university researchers. Success requires commitment and leadership at the highest level as well as a national strategy and plan that does the following:

- coordinates agency research and technology goals, budgets, and expenditures with national environmental goals and international standards endorsed by the federal government
- periodically reassesses environmental goals and related research programs to ensure that they reflect current understandings of the impact of specific aircraft emissions on the environment and human health
- takes advantage of the unique expertise of both government and industry personnel and reverses the current trend of lessening industry involvement in NASA-sponsored environmental research and technology development
- reallocates funds in accordance with long-term goals, shifting some resources from short-term mitigation in localized areas to the development of engine, airframe, and operational/air traffic control technologies that will lead to aircraft that are quieter, operate more efficiently, and produce fewer harmful emissions per revenue-passenger-kilometer
- supports international assessments of the effects of aircraft emissions and the costs and benefits of various alternatives for limiting emissions
- expedites deployment of new technologies by maturing them to a high technology readiness level (i.e., technology readiness level 6, as defined by NASA) and providing incentives for manufacturers to include them in commercial products and for users to purchase those products

Aviation is critically important to individuals, the economy, and the nation, yet the U.S. aviation industry has struggled with serious capacity issues, conflicting expectations regarding delays and environmental impacts, and long-standing federal policies on the expenditure of funds that limit support for the very research that is the key to long-term success. Vigorous federal leadership is essential to overcome funding restrictions and political issues and ensure that research and technology development proceeds as rapidly as is scientifically possible.

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1

Contemporary Realities of Aviation, the Economy, and the Environment

INTRODUCTION

Flight through the air—by insects, birds, or airplanes—requires sufficient power to overcome the forces of gravity and drag. Since that first flight at Kitty Hawk in 1903, aviation has advanced at an astonishing rate to become a key component of developed economies and societies. Because of the success of aviation, aircraft operations consume increasing amounts of fuel and produce more emissions and noise. Today, the environmental impacts of aircraft, mainly engine noise and emissions, are a small but significant fraction of the total consequences of fossil fuel consumption. In the future, expected growth in the aviation sector, as well as the larger impact of some emissions when they are released at higher altitudes, will make aviation noise and emissions increasingly significant here and in other countries.

The list of contemporary and future environmental issues that aviation must address includes the following:

- takeoff and approach noise (which present different technological problems for subsonic and supersonic aircraft)
- flyover noise from cruise altitudes in very quiet areas
- sonic booms and hyperbooms (i.e., the thermospherically refracted and very low intensity remains of sonic booms)
- taxi and engine run-up noise
- fuel venting and fuel dumping
- emission of CO, hydrocarbons, and NO_x in the airport area (below 3,000 feet)
- contrail formation
- emissions of CO_2
- emissions in the upper troposphere and stratosphere (from both subsonic and supersonic aircraft) of water vapor, NO_x, sulfur particles, and carbon particles
- potential for greenhouse effects and depletion of stratospheric ozone

As discussed in Box 1-1, federal responsibilities for controlling the environmental effects of aviation reside primarily with the Environmental Protection Agency (EPA), the Federal Aviation Administration (FAA), and the National Aeronautics and Space Administration (NASA).

The roar of a single jet transport taking off or passing close overhead seems to generate more complaints than some other sources of noise that are just as loud but more familiar. Objections to noise are preventing the expansion of some airports and are constraining operations, and noise is most frequently cited by officials at the nation's 50 busiest airports as their major environmental concern (see Figure 1-1).[1]

Aviation provides significant national benefits to the United States—

- as an engine of commerce and social interaction, transporting people and goods rapidly and safely on diverse missions all over the world
- as a vigorous sector of the economy that provides direct economic benefits by generating jobs and exports in the design and manufacture of engines, airframes, and avionics used by airlines, airports, and associated industries

It is clearly in the best interests of the United States and other nations that their aviation industries grow and prosper at the same time that aviation's impacts on the environment are reduced. The importance of federal action to maintain the vitality of the aviation enterprise while reducing adverse environmental impacts was recognized by the National Science and Technology Council in a 1995 report, which

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[1] As indicated by Figure 1-1, water quality and land use issues are also important at some airports. However, this study is focused on environmental issues that are most directly associated with aircraft technologies (i.e., noise and emissions).

BOX 1-1 Federal Responsibilities

In general, the EPA is responsible for the establishment and enforcement of U.S. environmental protection standards consistent with national environmental goals. For aircraft, however, the FAA is responsible for enforcing EPA clean air standards—by issuing Federal Aviation Regulations (FARs) that define how clean air standards will be applied to specific aircraft (Clean Air Act of 1970, as amended, 42 U.S.C. §7571).

With regard to standards for noise and sonic boom, the EPA must submit proposed aircraft noise control regulations to the FAA. The FAA then seeks public comment and either issues new regulations or publishes a notice explaining why new regulations are not appropriate. In making such a decision, the FAA must consider whether the standard or regulation proposed by the EPA is "consistent with the highest degree of safety in air transportation . . . [and] economically reasonable, technologically practicable, and appropriate for the applicable aircraft" (Noise Control Act of 1972, as amended, 42 U.S.C. §4902; and 49 U.S.C. §44715).

The role of NASA is to increase the range of options that are technologically feasible. NASA is charged with conducting aeronautical research and development, including long-range studies of potential problems and benefits, to preserve "the role of the United States as a leader in aeronautical . . . technology." NASA is also expected to "carry out a comprehensive program of research, technology, and monitoring of the phenomena of the upper atmosphere so as to provide for an understanding of and to maintain the chemical and physical integrity of the Earth's upper atmosphere." Industry and academia are expected to participate in this research, and the results are to be given to appropriate regulatory agencies to assist them in generating new standards and regulations (National Aeronautics and Space Act of 1958, as amended, 42 U.S.C. §2451).

warned that "environmental issues are likely to impose the fundamental limitation on air transportation growth in the 21st century" (NSTC, 1995). In response, federal agencies have identified noise and emissions targets for the next few decades and are pursuing a research agenda intended to achieve the linked goals of supporting the growth of aviation and reducing environmental impacts. The present report offers recommendations intended to increase the effectiveness of that agenda and the associated research efforts.

ENERGY CONSUMPTION AND ITS CONSEQUENCES

The adverse environmental effects of jet aircraft are primarily a consequence of the combustion of petroleum. Jet fuel is largely carbon and hydrogen, and so combustion releases carbon dioxide (CO_2). Other gases, including oxides of nitrogen (NO_x), are also produced by chemical interactions with the air flowing through the engine. Water vapor emitted by the engine combines with water vapor already

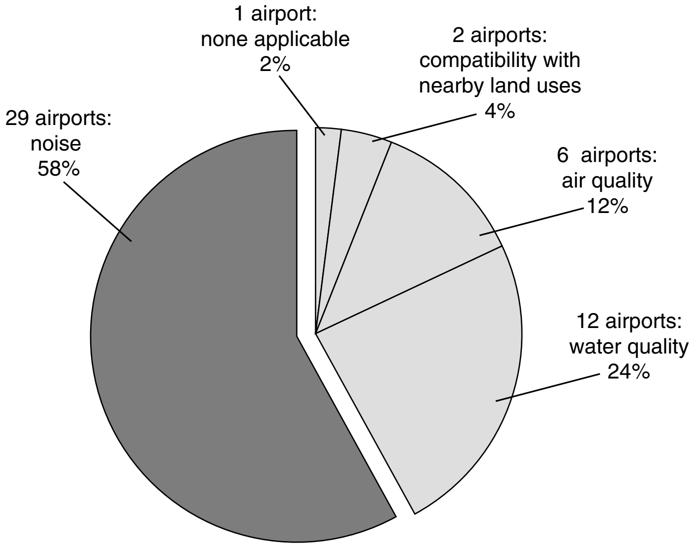

FIGURE 1-1 Environmental issues that most concern officials at the 50 busiest U.S. airports. SOURCE: GAO, 2000.

TABLE 1-1 U.S. Energy Consumption Fractions, 1999

Energy Source	10^{15} Btu	Percent of Total
Petroleum for jet fuel	3.2	3.4
Renewable energy	7.4	7.6
Coal	21.7	22.5
Natural gas	22.1	22.9
Petroleum total	37.7	39.0
Fossil fuel total	81.6	84.4
Total energy	96.6	100.0

SOURCE: EIA, 2002a.

present in the atmosphere and sometimes freezes to form condensation trails (contrails) behind the aircraft. Under some atmospheric conditions, ice crystals in the contrails grow and disperse, increasing the amount and intensity of regional cirrus clouds and modifying the atmospheric radiation budget that controls average global temperatures. With respect to aviation noise, the internal noises of the turbine engines combine with the noise generated by the jet exhaust and the rush of air over the airframe itself.

The major forms and amounts of energy used by the U.S. economy and trends for consumption are given in Table 1-1 and Figure 1-2. Between 1989 and 1999, the United States increased its consumption of natural gas (14 percent), petroleum (10 percent), and coal (15 percent). The consumption of jet petroleum increased by 10 percent, and the consumption of petroleum products by the entire transportation industry increased by 14 percent. In 1999, all transportation sectors combined accounted for approximately 22 percent of energy consumption. Jet fuel accounted for approximately 13 percent of the transportation total, with automotive gasoline accounting for 66 percent and diesel fuel oil accounting for 20 percent. Jet petroleum represented 3 percent of total U.S. energy consumption, indicating that the environmental effects of aviation must be small compared with those caused by other users of fossil fuels. The demand for jet petroleum is increasing steadily, consistent with the overall growth in demand for energy.

Finding 1-1. Increasing Rate of Fuel Consumption. Fuel consumption is a key indicator for assessing trends in emissions. The aviation industry is growing and the use of aviation fuel is increasing at a rate comparable to that of other uses of fossil fuels.

Recognizing that reductions in fuel consumption rates are advantageous from both economic and environmental perspectives, industry has increased the efficiency of aircraft engines and aircraft. Indeed, the amount of fuel consumed per revenue-passenger-kilometer has been considerably re-

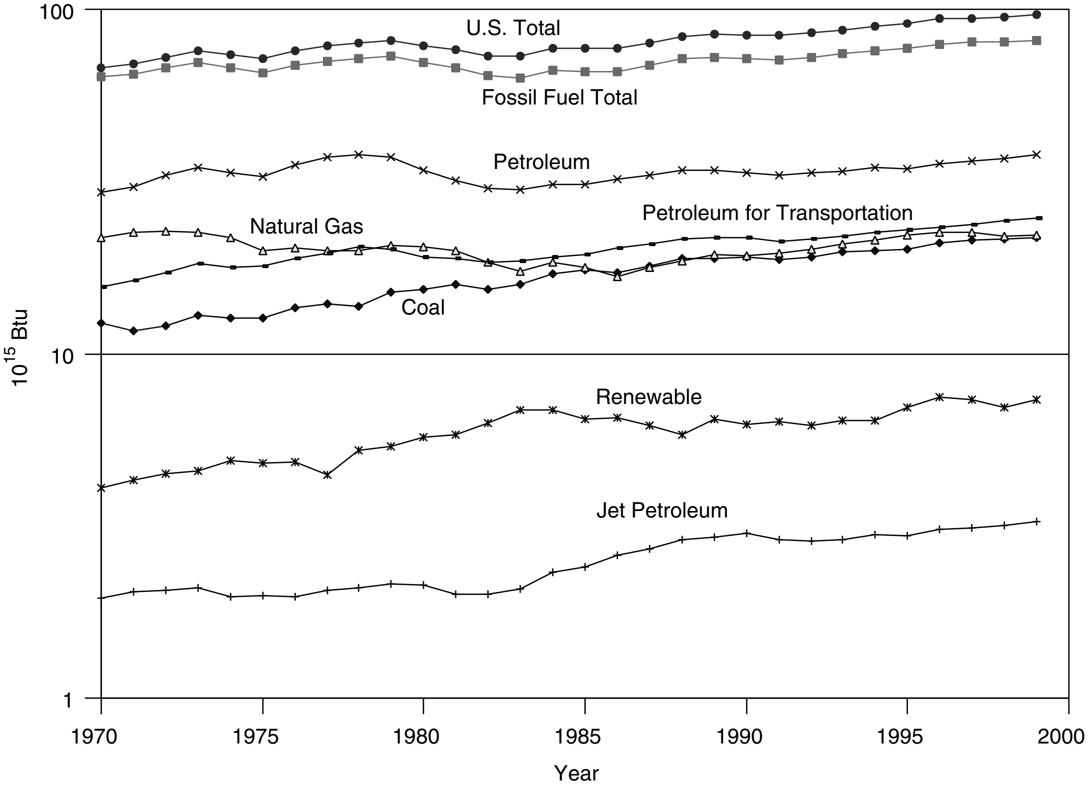

FIGURE 1-2 Sources of energy in the United States. SOURCE: EIA, 2002b.

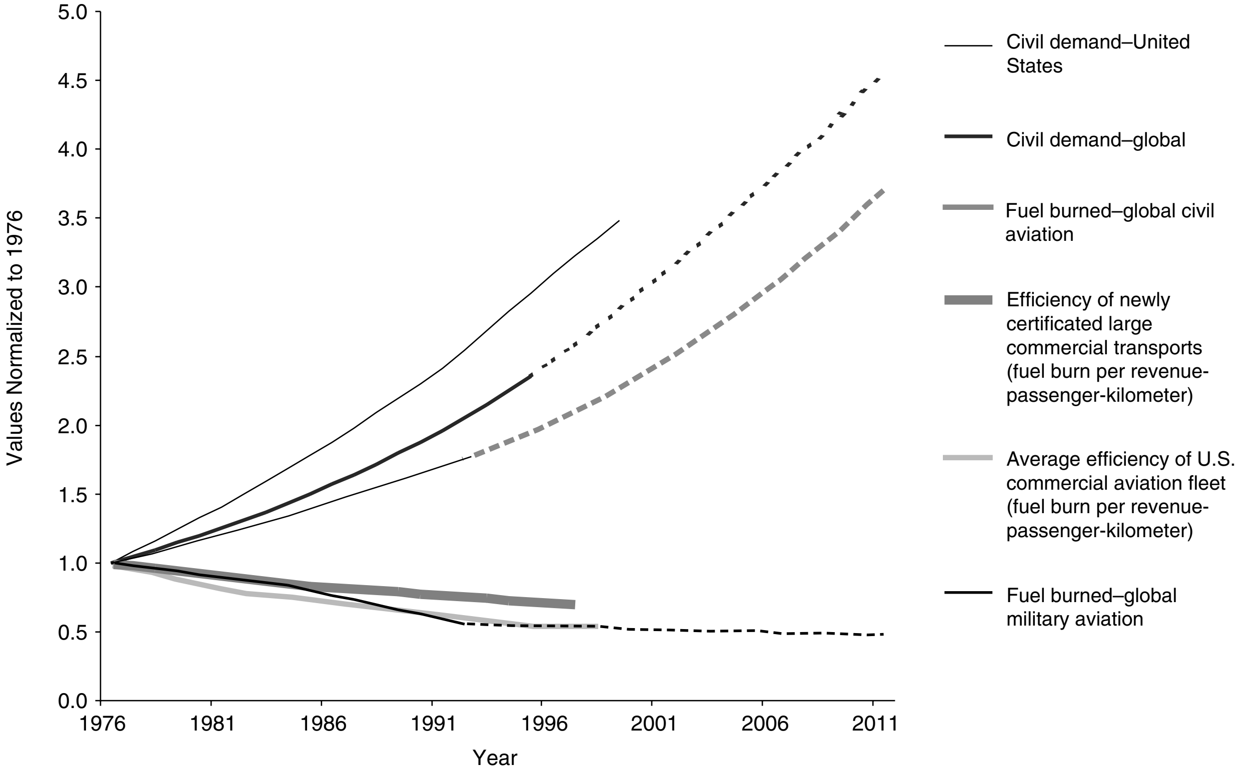

FIGURE 1-3 Decadal trends for demand, efficiency, and fuel usage. Dashed portions of curves are projections. SOURCE: Lukachko and Waitz, 2001.

duced since the advent of commercial jet transports, albeit at a slowing rate of improvement in recent years. As indicated in Figures 1-3 and 1-4, however, the growth in demand for commercial air transportation has consistently exceeded increases in fuel efficiency.[2] The problem is becoming more serious as efficiency improvements become technologically more difficult to achieve. Continued improvements remain essential, however. U.S. demand for air transportation tripled between 1977 and 1996 and is expected to double in the next 15 to 20 years. To maintain the status quo in terms of environmental impact, fuel consumption per passenger-kilometer must be cut in half, but government and industry have done only a little better than that in the entire 40-year history of commercial jet aviation. Dramatic new improvements are essential, but they are likely to be achieved only with a vigorous research and technology program that yields advances not yet foreseen.

Globally, in 1976 military aviation consumed about 55 percent of all aviation fuel. As shown in Figure 1-3, military demand has been dropping as commercial demand has increased, and in 1996 military demand for aviation fuel was only 16 percent of the global total. General aviation consumes a much smaller fraction of aviation fuel, globally and nationally. This study focuses on commercial aviation.

The situation is similar with respect to aircraft noise: aircraft performance has improved, but not as fast as demand has increased. Part 36 of the Federal Aviation Regulations covers noise requirements that aircraft must meet for FAA certification. Since it was issued in 1969, Part 36 has been amended more than 20 times and now covers virtually all types of aircraft. Several of these amendments have instituted more stringent noise requirements. On two occasions, amendments required large numbers of aircraft that could not meet new noise restrictions to be phased out of operation even though they were still flightworthy. New, stricter regulatory requirements are expected in the future as a result of ongoing action by the International Civil Aviation Organization (ICAO), which takes the lead in setting international

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[2] Future demand for air transportation depends upon a wide variety of factors, including the general state of the economy. Figure 1-4 depicts expected outcomes for two different demand scenarios. Between 2000 and 2015, Scenario 1 assumes that growth in passenger air travel will average about 5 percent per year, and Scenario 2 assumes a growth of about 3 percent per year. The FAA predicts that domestic air travel on U.S. airlines will increase about 4 percent per year between 2000 and 2012, down from the 5 percent growth per year experienced between 1995 and 2000 (FAA, 2001). Limitations on growth associated with environmental concerns and airport and airway capacity, however, may prevent the air transportation system from meeting future demand.

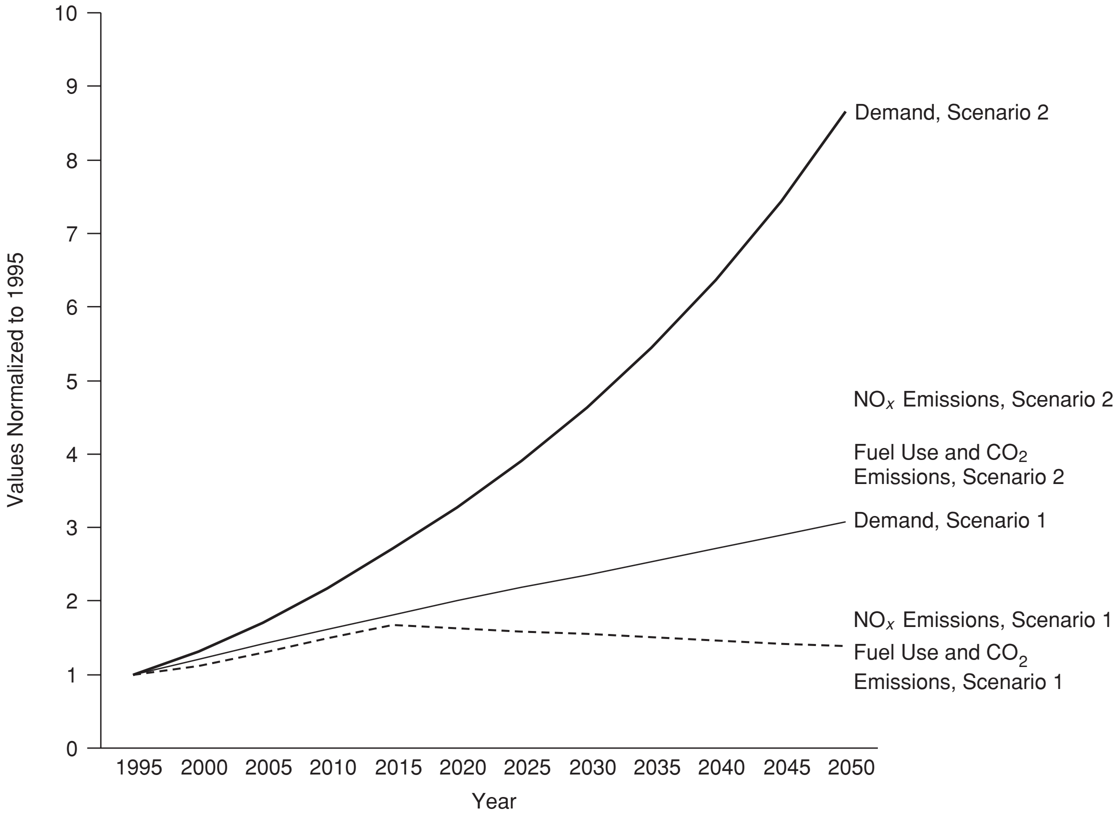

FIGURE 1-4 Effects of demand (in terms of revenue-passenger-kilometers) on the production of NO_x and CO_2 and on fuel consumption. The curves show the boundaries created by scenarios with the least and greatest demand projections. SOURCE: Prather and Sausen, 1999, and Henderson and Wickrama, 1999.

standards that many nations, including the United States, subsequently adopt as national standards.

Because of advanced technology, the perceived noise level produced by new commercial jet aircraft of a given size has been reduced by about 10 dB since the 1960s, which is equivalent to reducing annoyance by roughly a factor of 2 (FAA, 1997). These improvements have resulted primarily from technological advances that were incorporated into more economical aircraft and propulsion systems. Despite these improvements, noise is becoming more of a problem for several reasons:

- The amount of air traffic is growing.
- The number of very large aircraft is increasing (for a given level of technology, one large aircraft generally produces a higher noise level than several smaller aircraft with the same total passenger capacity).
- The hub-and-spoke routing system used by most airlines concentrates a lot of traffic and noise at a relatively small number of airports.
- Public acceptance of noise is diminishing.

Community concerns about noise and other environmental effects result in airport curfews, flight path restrictions, and delayed or canceled airport expansions. Three-quarters of the delays experienced by expansion projects at the 50 busiest U.S. airports are primarily because of environmental issues, and 12 of the 50 busiest airports have had at least one expansion project canceled or indefinitely postponed because of environmental issues (GAO, 2000). The results are congestion, flight delays, and, on occasion, diversions and cancellations when aircraft are delayed so long that they would arrive at their destination airport after a curfew. The current situation is expected to deteriorate; during the next 6 years alone, the number of large U.S. airports operating at or above capacity is expected to more than double (see Table 1-2).

TABLE 1-2 Estimated Time for the 50 Busiest U.S. Airports to Reach Capacity

Estimated Time	Number of Airports
Already at capacity	13
1 to 2 years	4
3 to 4 years	7
5 to 6 years	8
7 to 9 years	2
10 or more years	11
Other	5

SOURCE: GAO, 2000.

REGULATORY GOALS

ICAO tries to harmonize international regulatory standards for aircraft noise and emissions by recommending appropriate standards that regulatory bodies around the world can adopt. Intervention by local and regional groups, however, has made this process ineffective in providing a common set of rules. Airports and airlines face sometimes-differing restrictions imposed by local and national governments and multinational bodies such as the European Union. The operational impact of such restrictions, as well as the rate at which they are changing and the extent to which they are aligned with ICAO standards, varies widely around the world. Often, several different sets of regulations apply to a flight in a single airport area, with different standard-setting bodies having jurisdiction over different environmental impacts, but with little or no coordination among them.

As a consequence of differing standards, conflicts arise. One locality may emphasize low-noise takeoffs and landings, but the lower noise flight path and lower engine power settings may result in aircraft spending more time at low altitude, which increases the effects of aircraft emissions on ground-level air quality. To address these conflicts, the federal government should carry out its responsibilities for mitigating the environmental effects of aircraft noise and emissions with a balanced approach that includes commitment and leadership at the highest level and cooperation among federal, state, and local governments; industry; and public and private research organizations. To ensure that regulations protect the public without unnecessarily constraining the availability of air transportation services, the federal government must also support research to develop a comprehensive perspective on the environmental effects of aviation and how they can be mitigated or accommodated.

INDUSTRY RESPONSES AND RESPONSIBILITIES

Regulatory and economic incentives are too small—and the technical challenges too large—for industry acting alone to eliminate the environmental effects of growth in air travel. The development of environmental protection technologies that reduce noise and emissions from aircraft is what economists term “externalities” in air travel. Manufacturers have little or no motivation to pay for developing aircraft that are quieter or produce less emissions than required by regulation unless they can recoup the additional expense by selling cleaner, quieter airplanes at a higher price (or by selling more of them). Airlines, however, have little or no motivation to pay more for quieter, cleaner aircraft if their customers—the traveling public—do not consider noise and emissions important in selecting an airline. Even if air travelers would fly preferentially on quieter or lower-emission aircraft, information is not available to allow them to make informed decisions. Like manufacturers and airlines (and most other successful businesses), airports focus on meeting the demands of their paying customers (i.e., airlines and passengers). As a result, environmental compatibility tends to fall to the bottom of everyone’s list of priorities—except for people with a special interest in the environment, especially those who live close to an airport (see Table 1-3 for the committee’s perception of priorities). Although all agree that the environment is important, in the highly competitive air transportation industry environmental performance is not as critical as safety or economics (as long as aircraft are clean and quiet enough to meet regulatory standards). Industry by nature responds to economic and regulatory incentives created by governments and the public. Thus, it falls to governments and regulatory bodies, acting on behalf of the public, to ensure that aviation growth is as environmentally compatible as possible.

TABLE 1-3 Perceived Priorities of Consumers and Industry

Passenger Priorities When Purchasing Airline Tickets[a]	Airline Priorities for Meeting Passenger Preferences	Airport Priorities for Meeting Airline and Passenger Preferences	Manufacturer Priorities for Meeting Airline Preferences
1. Safety and security 2. Ticket price 3. Frequent flyer benefits 4. Schedule and trip length 5. Comfort 6. On-time performance 7. Environmental impact	1 Safety and security 2. Reliability 3. Economics a Aircraft compatible with airlines’ route system b. Cost per seat-kilometer (durability, cost of maintenance, fuel burn, etc.) 4. Passenger convenience a. In-flight entertainment b. Seat comfort c. Cabin noise d. Other 5. Environmental impact[b]	1. Safety and security 2. Adequate capacity and dispatch reliability a. Runways b. Air traffic control c. Gates and terminals d. Ice and snow removal (depending on climate) e. Parking f. Ground access 3. Economics 4. Environmental impact[b]	1. Safety 2. Reliability 3. Durability (airframe fatigue) 4. Economics a. Passenger ticket cost b. Airline profitability c. Manufacturer profitability 5. Passenger comfort 6. Environmental impact[b]

[a] Priorities can vary among different groups of passengers. For example, schedule and trip length are often a higher priority than ticket price among business travelers.

[b] Environmental impact is a low priority unless mandated by regulation; then it goes up on the list.

TABLE 1-4 NASA's Goals for Reducing the Environmental Effects of Future Aircraft (percentage reductions compared with levels that existed in 1997)

Reduction in	By 2007	By 2022
Noise	50%	75%
NO_x emissions	70%	80%
CO_2 emissions	25%	50%

SOURCE: NASA, 2002.

There are interesting contrasts to the industry attitudes toward safety and environmental requirements. All involved know that meeting expected levels of safety and security are absolutely top priorities and that bearing the necessary costs is essential to staying in business. As societal demands for reducing adverse environmental impacts become more strident, the priority attached to environmental compatibility will likely rise. But there are significant differences between safety and environmental engineering. Safety engineering in aviation is a well-established field, and the length of time between identification of a safety need and implementation of required changes is typically on the order of a few years—except in the case of urgent needs. On the other hand, achieving the ambitious goals set by NASA for environmental compatibility (see Table 1-4) is likely to take decades and require large investments in new, high-risk technologies with uncertain payoffs. Individual technology development programs may require on the order of $100 million before it is possible to learn whether the results justify further investment in flight demonstration hardware. This kind of high-risk, extremely long-term research and technology investment is incompatible with normal corporate research practices, which are typically aimed at commercial payoffs within a few years. The fact that individual companies suffer no short-term adverse consequences for *not* investing in environmental compatibility research also tends to discourage them from doing so.

SUPERSONIC AIRCRAFT

A large commercial supersonic aircraft with a cruise speed of Mach 2 to 2.4 has about twice the drag and burns more fuel per passenger-kilometer than a large subsonic aircraft with an equivalent level of technology. Also, the most efficient cruise altitude for aircraft becomes higher as cruise speed increases. Commercial supersonic aircraft with cruise speeds of about Mach 2 or higher will likely cruise in the stratosphere, where the effects of aircraft emissions on the environment can be much greater than at lower altitudes (in the troposphere) frequented by subsonic aircraft. Even water vapor, which is benign in the troposphere (unless it forms a contrail), may contribute to ozone depletion and global warming when exhausted into the stratosphere. From a fleetwide, climate-change perspective, this would be a problem if a large number of commercial supersonic aircraft were built. However, that is not likely in the next 25 years (NRC, 2001). In addition, the uncertainty of current atmospheric models is still substantial; carefully researched estimates of the impact of stratospheric water vapor on climate vary by a factor of about 3.

The next step in the development of commercial supersonic aircraft may be the development of a supersonic business jet that would be much smaller, consume much less fuel, and operate in smaller numbers than would the fleet of large supersonic aircraft postulated in previous studies. Another alternative would be to develop a large commercial aircraft with a cruise speed close enough to Mach 1 that the aircraft could be designed to (1) incur a significantly smaller drag penalty than a Mach 2 aircraft and (2) avoid creating a sonic boom that would propagate to the ground. Boeing is currently conducting design studies of such an aircraft.

When future supersonic aircraft enter service they may need to meet the same community noise standards as subsonic aircraft. Also, Federal Aviation Regulations prohibit commercial supersonic aircraft from producing a sonic boom over land. Those regulations are unlikely to be revised except, perhaps, to allow sonic booms at such low intensities that they do not create a public nuisance. The ability to fly at supersonic speeds over land would greatly improve the utility of supersonic aircraft, but research is needed both to determine what level of sonic boom might be acceptable and to develop a practical technological approach for achieving it.

For the foreseeable future the vast majority of commercial air travel will be via subsonic aircraft, and the environmental impact of aviation will be determined by the noise and emissions produced by these aircraft. Therefore, this study focuses on subsonic aircraft. Additional information related to supersonic aircraft, including findings and recommendations, appears in reports published by the National Research Council (NRC, 1997, 1998, 1999, 2001) and the Intergovernmental Panel on Climate Change (IPCC, 1999).

RESEARCH STRATEGIES

The U.S. air transportation system is a critical industry and an invaluable national resource now caught between two powerful but conflicting expectations: the first for more services, the second for decreased environmental impact. The two demands can be reconciled only through a systematic approach that provides the following:

- a better understanding of the scientific issues involved
- realistic goals that avoid raising false expectations
- a comprehensive research strategy that provides advanced technologies for dramatically improving engine and airframe performance
- enhancements to the other portions of the air transpor-

tation system (e.g., the air traffic control system) to improve operational efficiency

Urgent action is essential for several reasons:

- Environmental issues are already interfering with the efficient operation of the U.S. air transportation system.
- Air traffic is increasing.
- Environmental standards are becoming more stringent.
- Research and technology development takes a long time to change the face of commercial aviation.

New technology may take 10 years or more to be proven commercially acceptable and certified by the FAA for use on commercial aircraft. In addition, the production run on a successful aircraft may last for 15 to 20 years, and individual aircraft may have service lives of 25 to 35 years. As a result, it can take decades for a major technological improvement to show up in a majority of the commercial fleet unless it can be retrofitted into existing aircraft at reasonable cost.

Given the current funding available, the Committee on Aeronautics Research and Technology for Environmental Compatibility has concluded that federal research programs in noise reduction technology are focused appropriately. However, much remains to be done, and uncertainties persist in many areas. In collaboration with other stakeholders (such as manufacturers, airlines, airport authorities, local governments, nongovernmental organizations, and foreign regulatory bodies and researchers), NASA and the FAA should support research to resolve uncertainties in the following areas:

- long-term atmospheric effects of aircraft emissions locally, regionally, and globally
- reliable goals for noise and emissions reductions for each phase of flight
- the optimum long-term strategy for improving the understanding of the many specific issues, including economic factors, associated with aircraft noise and emissions

Economic analyses must form a key element in much of the research in the above areas because economic incentives for providers and users of air transportation equipment and services are likely to be a key component of a successful long-term strategy.

NASA and other agencies should sustain promising research long enough to ensure that new technology developed by federal research programs is mature enough to warrant commercial development. This will require a balanced allocation of federal funds devoted to mitigating the environmental effects of aviation. In particular, federal expenditures to reduce noise should be balanced between abatement of noise at specific airports (e.g., through soundproofing of privately owned buildings located outside the airport perimeter) and the development of advanced aircraft technologies that will ultimately reduce aircraft noise globally.

Finding 1-2. Vigorous Action Required. Environmental concerns will increasingly limit the growth of air transportation in the 21st century unless vigorous action is taken to augment current research and technology related to the environmental impacts of aviation.

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2

Noise

Despite extensive growth in air transportation over the last several decades, advanced technologies and more stringent regulatory standards have greatly reduced the number of people adversely affected by noise. Unfortunately, this trend is unlikely to continue, and public opposition to airport noise is becoming more—not less—of an impediment to the growth of the air transportation system. Even though fewer people are exposed to high levels of aviation noise, local communities still experiencing levels that residents perceive as unacceptable are increasingly willing to oppose expansions of airport facilities and operations. Although NASA's noise reduction goals are appropriate and additional technological advances are possible, the level of funding for federal research programs is too low to achieve the goals on schedule (see Table 1-4) or to remove noise as an impediment to the growth of aviation. The vast majority of federal expenditures on aviation noise are allocated to noise abatement at individual airports rather than to research on quieter engines and aircraft, which would ultimately reduce aviation noise nationally and internationally. More effective interagency coordination and a more balanced allocation of funds would support a vigorous and comprehensive research program that could mature a wider array of promising technologies and reduce the time it takes for new technology to become prevalent in the commercial fleet.

TRENDS IN AVIATION NOISE

As indicated in Chapter 1 and Figure 1-1, noise is the single greatest environmental concern facing air carriers and airports today. Officials at 29 of the 50 busiest U.S. airports asserted that noise from airport operations was their most serious environmental concern, and officials from 22 of the airports stated that noise will remain the top concern in the future because of expected increases in operations and in the number and stringency of noise restrictions (GAO, 2000). Noise concerns limit aviation capacity by delaying runway expansion (see the example in Box 2-1) and causing flight cancellations and delays on a daily basis (see Box 2-2 for three typical examples from a single airline during a week in January 2000). The net result is higher airline operating costs and higher ticket prices. Further, noise is often a principal focus for community groups and larger nongovernmental organizations that act to oppose runway expansion.

Part 36 of the Federal Aviation Regulations, which defines aircraft certification requirements related to noise, was issued in 1969, and federal legislation aimed at reducing the annoyance associated with aviation noise sources was first enacted in 1972 (Noise Control Act, P.L. 92-475). Since that time, a variety of technological and operational advances have led to a reduction in the average perceived noise from a single aircraft operation of greater than 10 EPN dB (effective perceived noise level in decibels—a measure of aircraft noise that is closely linked to levels of human annoyance).[1] Note that a reduction of 10 EPN dB corresponds to roughly 50 percent less annoyance for a single event. Figure 2-1 shows centerline takeoff noise levels measured during FAA certification tests for individual aircraft as a function of the date at which the aircraft model was certified. (During certification, an aircraft must also meet certification standards for sideline takeoff noise and approach noise.) The large reduction in noise in the late 1960s and early 1970s was a result of the introduction of the turbofan engine. While the primary motivation for the use of turbofan engines was reduced fuel consumption, less noise was an important ancillary benefit. In the 1980s and 1990s, changes were more evolutionary, with increased by-pass ratio engines, better

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[1] For detailed information on how effective perceived noise level is measured, see Appendix B of Federal Aviation Regulations Part 36—Noise Standards: Aircraft Type and Airworthiness Certification, which is codified in 14 CFR 36 and available online at <http://www.access.gpo.gov/nara/cfr/cfrhtml_00/Title_14/14cfr36_00.html>.

BOX 2-1 Example of Delays in Runway Expansion Due in Part to Aviation Noise

In the early 1970s, MASSPort, the public authority that manages Logan International Airport in Boston, attempted to add a runway, runway 33R/15L, to parallel existing jet runway 33L/15R. Construction started, but members of the community blocked the bulldozers and stopped the work. As a result, MASSPort was enjoined by the court from constructing any more runways. The injunction is still in effect today. As a result of the incomplete construction effort, runway 33R/15L exists, but it is only 2,557 feet long—too short by far to handle large jet aircraft.

From 1975 to 2000, Logan's total operations increased from about 300,000 to 500,000 takeoffs and landings per year. Within the past 2 years, MASSPort proposed a new, 5,000-foot runway, runway 14/32, to be located at the southern edge of the airport. This runway would service smaller aircraft (commuter and light aircraft), which currently constitute 40 to 50 percent of Logan's operations. It would also be unidirectional in that the only operations permitted would be landings on 32 and departures on 14. The local community has also opposed construction of this runway.

SOURCE: Personal communication, Nancy Timmerman, Manager, Noise Monitoring Systems, Massachusetts Port Authority, February 2001.

BOX 2-2 Examples of Flight Delays and Cancellations Directly Caused by Aircraft Noise Restrictions

January 5, 2001. Delta Air Lines Flight 1285 left John F. Kennedy International Airport in New York City with 98 passengers bound for Ronald Reagan Washington National Airport, in Washington, D.C., and 31 passengers bound for Atlanta. Flight 1285 was late departing New York because weather conditions required de-icing prior to takeoff. As a result, the flight was unable to reach Washington, D.C., until after the noise curfew at National Airport. Therefore, Flight 1285 was diverted to Washington Dulles International Airport, where an additional 32 passengers boarded the plane to go to Atlanta. Meanwhile, 33 passengers at National Airport who had been booked for the leg to Atlanta had to make other arrangements.

January 7, 2001. Delta Flight 198 was scheduled for a night flight from San Diego to Cincinnati with 38 passengers. The flight crew was on another flight that was late arriving in San Diego. As a result, Flight 198 had to be canceled because it was unable to take off prior to the noise curfew at San Diego International Airport.

January 11, 2001. Delta Flight 1670 was scheduled to fly from San Diego to Dallas/Fort Worth. The aircraft needed for this flight should have arrived in San Diego the previous evening as Flight 2115 from Salt Lake City. That flight, however, and its 58 passengers had been diverted to Los Angeles, apparently because of the noise curfew (coupled with "field conditions") at San Diego International Airport. Delta Air Lines used a bus to get the passengers on Flight 2115 to San Diego after they deplaned at Los Angeles, and Flight 1670 was canceled on the following morning because no aircraft were available in San Diego.

acoustic liner technology, and other engineering changes being gradually introduced. The development of many of these improvements was supported by NASA research programs. Between 1970 and 2000, average aircraft capacity increased from 113 seats to 158 seats, and the average number of engines per aircraft dropped from 3.2 to 2.3 (averages are weighted by distance traveled by different aircraft). Larger aircraft with fewer engines require engines with more thrust, which produce more noise, and this has offset some of the technological gains. The differences between the noise levels of the various aircraft shown in Figure 2-1 arise from differences in technology level, overall size and weight, and number of engines. Variations due to size and/or weight and number of engines are accounted for in the certification regulations: heavier aircraft with more engines are generally allowed higher noise levels.

Figure 2-1 indicates that the pace of technological change has been roughly constant—an improvement of about 3 dB per decade—over the past 40 years. ICAO's Committee on Aviation Environmental Protection has recently recom-

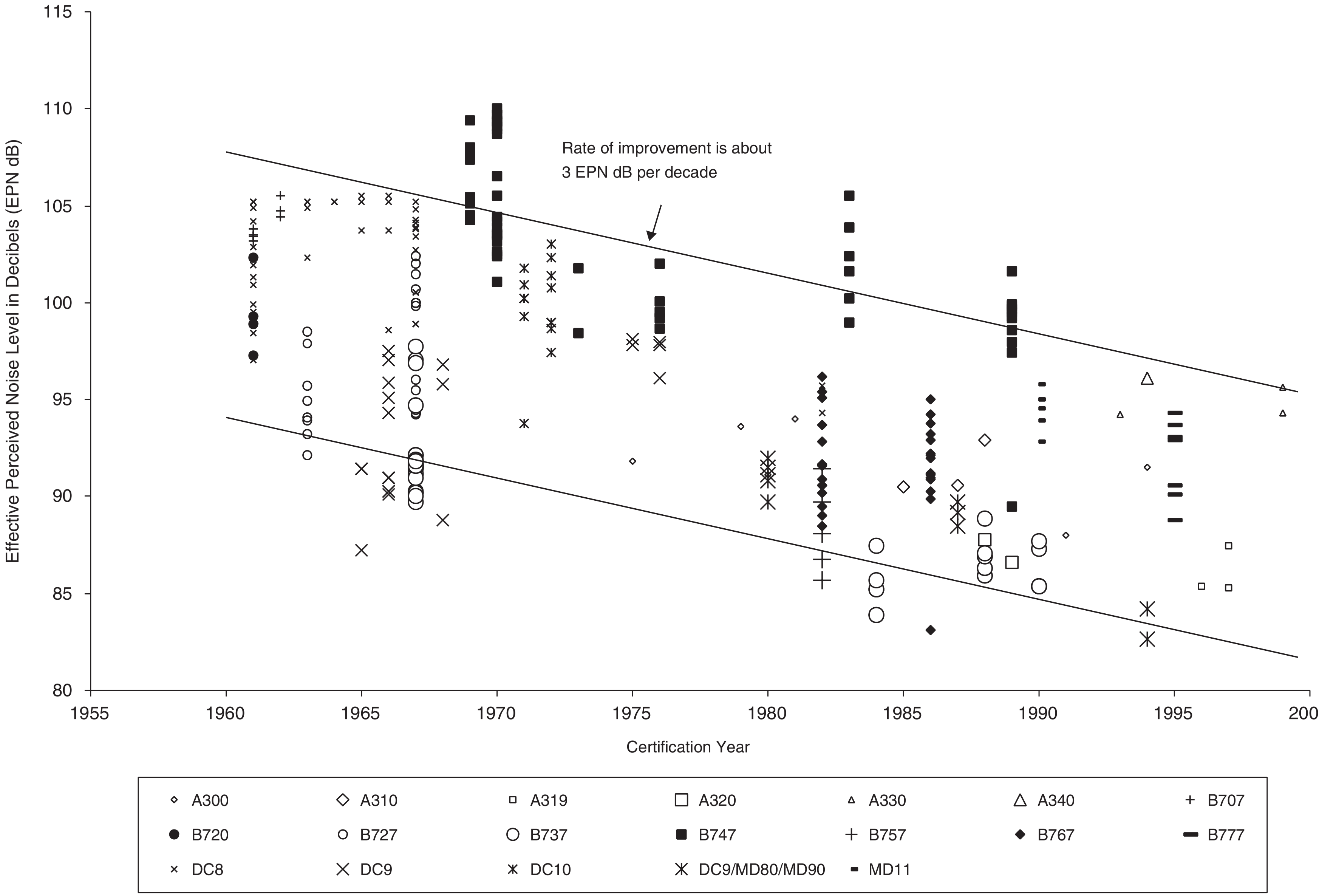

FIGURE 2-1 Trends in aircraft noise levels: effective perceived noise level during takeoff for aircraft at maximum takeoff weight as a function of certification date. SOURCE: Lukachko and Waitz, 2001.

TABLE 2-1 Effects of Noise on People

DNL (dB)	Qualitative Description of Potential for Hearing Loss	Percent of Population Highly Annoyed	Average Community Reaction	General Community Attitude
75 and above	Hearing loss may begin to occur	>37	Very severe	Noise is likely to be the most important of all adverse aspects of the community environment
70	Hearing loss not likely	22	Severe	Noise is one of the most important adverse aspects of the community environment
65	Hearing loss will not occur	12	Significant	Noise is one of the most important adverse aspects of the community environment
60	Hearing loss will not occur	7	Moderate to slight	Noise may be considered an adverse aspect of the community environment
55 and below	Hearing loss will not occur	3	Moderate to slight	Noise considered no more important than various other environmental factors

SOURCE: FICON, 1992.

mended reducing the noise certification standard by 10 dB (cumulative), which is equivalent to reducing the noise at each of the three certification points (takeoff, sideline, and approach) by approximately 3 dB. In part, this reduction was recommended because it represents the current state of feasible technology.

Figure 2-1 shows the change in effective perceived noise for a single aircraft operation during certification tests. However, for assessing the noise impact of a specific airport on the local community, it is more useful to consider an appropriate average of the noise produced by the flight operations from that airport over a 24-hour period. One such measure is the day-night average sound level (DNL), a metric for assessing annoyance from aircraft noise that has been adopted by the FAA for aircraft noise compatibility planning. It is assumed in forming this measure that operations occurring at night are more annoying than those occurring during the day because of the potential for sleep disturbance and because background noise is lower at night. Therefore, DNL is weighted to count each takeoff or landing between 10 P.M. and 7 A.M. the same as 10 daytime takeoffs or landings of equal loudness.

A summary of personal responses to noise and their relation to DNL level is shown in Table 2-1. At 55 dB DNL (indoors or outdoors), noise is considered no more important than various other environmental factors, and only about 3 percent of the population affected will be highly annoyed by noise. At 60 dB DNL, research suggests that the annoyance rate will be approximately 7 percent, and noise *may* be considered an adverse aspect of the community environment. At 65 dB DNL, 12 percent of the population will be highly annoyed and noise *is* one of the important adverse aspects of the community environment. (It should be noted that the median outdoor exposure to noise in urban areas is 59 dB DNL, with a range of 58 to 72 dB.) Corresponding ranges for suburban and wilderness areas are 48 to 57 dB and 20 to 30 dB, respectively. Although areas with levels greater than 65 dB DNL are given priority for federal noise abatement funds, most complaints regarding aviation noise come from areas with a DNL less than 65 dB, because the number of people living in areas with a DNL of 55 to 65 dB may be 5 to 30 times the number of people living in areas with greater than 65 dB DNL; airports themselves occupy much of the land where the DNL is higher than 65 dB, whereas the land with DNLs between 55 and 65 dB is typically used for other commercial and residential purposes. Figure 2-2 shows the areas around San Francisco International Airport where the DNL exceeds 55 and 65 dB. The complexity of the issues surrounding public response to aviation noise is further articulated in Box 2-3.[2]

Success in preventing deviations from the “normal noise experience” can be a factor in reducing annoyance from aircraft noise. Atlanta’s Hartsfield International Airport, the world’s busiest, receives relatively few noise complaints from citizens who live under departure and approach paths, in part because flight crews and FAA controllers consistently keep aircraft following the specified flight tracks, thereby minimizing variation in noise levels that local residents have come to expect.

The number and duration of jet noise events can also affect levels of annoyance. Studies have shown that, on average, a 3-dB increase in noise level does not increase the level of annoyance if the noise lasts for half as long or half the number of noise events occurs.

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[2] For additional information on DNL and the development of noise exposure maps, see section 150.7 and Appendix A of Federal Aviation Regulations Part 150—Airport Noise Compatibility Planning, which is codified in 14 CFR 150 and available online at <www.access.gpo.gov/nara/cfr/cfrhtml_00/Title_14/14cfr150_00.html>.

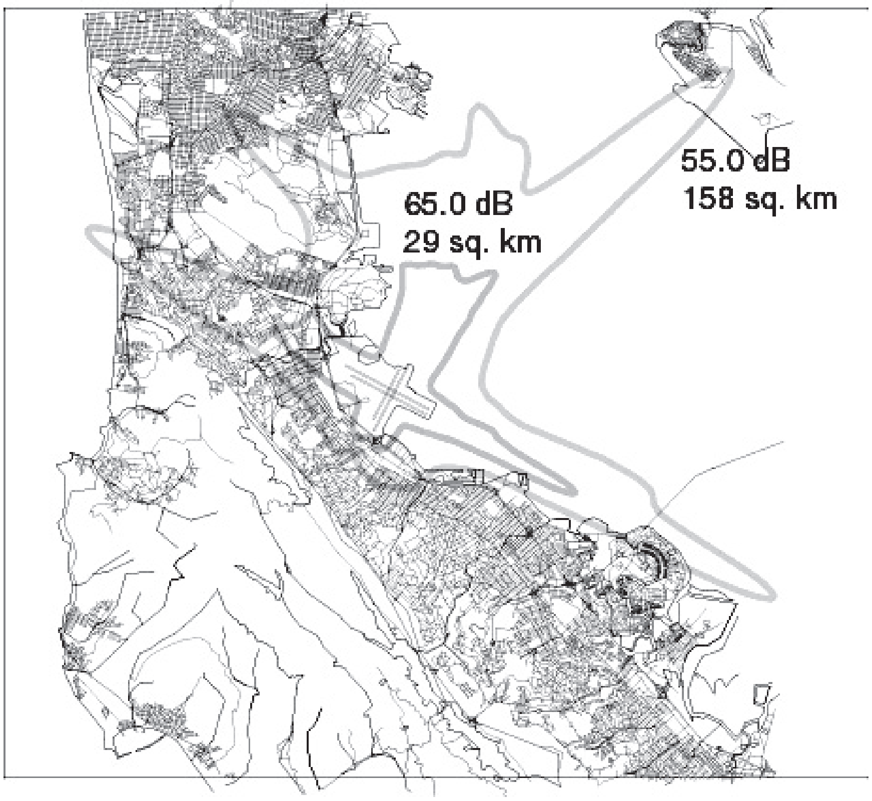

FIGURE 2-2 Extent of high-noise areas around San Francisco International Airport, 1998-1999. SOURCE: Fleming, 2001.

BOX 2-3 Aviation Noise Challenges

The FAA has estimated that domestic air travel will increase 3.6 percent annually between 2000 and 2011, for cumulative growth of almost 48 percent during that time period. To build the infrastructure necessary to accommodate that growth and to handle the additional aircraft it will bring, both the airline industry and local officials must address the concerns of citizens who live near, and in some instances considerable distances from, airports.

When air traffic patterns change, complaints may be received from citizens who live under the new flight paths, even if the noise is at relatively low levels. For example, in 1987 the FAA restructured the air routes in the northeastern United States, including the metropolitan New York City area. The purpose of the restructuring was to make more efficient use of the airspace and to enable continued growth at the region's airports. As a result of this airspace redesign, airplanes started flying over areas of New Jersey that had not previously had overflights. The noise heard on the ground from these flights was low compared with the standards for annoyance. However, a significant number of residents expressed (and 15 years later continue to express) great dissatisfaction with this situation. The reason given for their dissatisfaction is aircraft noise that they had not previously experienced.

As another example, many of the noise complaints that the new Denver International Airport receives are from residents 40 miles away, in the vicinity of Boulder. Prior to construction of the new airport, its location was not considered to present a noise annoyance problem because the closest residential areas were nearly 10 miles away. Parts of the Boulder area, however, are isolated from both industrial and highway noise, and the relatively quiet environment makes a jet at 10,000 feet seem noisy when it passes overhead at climb thrust, particularly because residents had not experienced jet traffic overhead before the opening of the new airport.

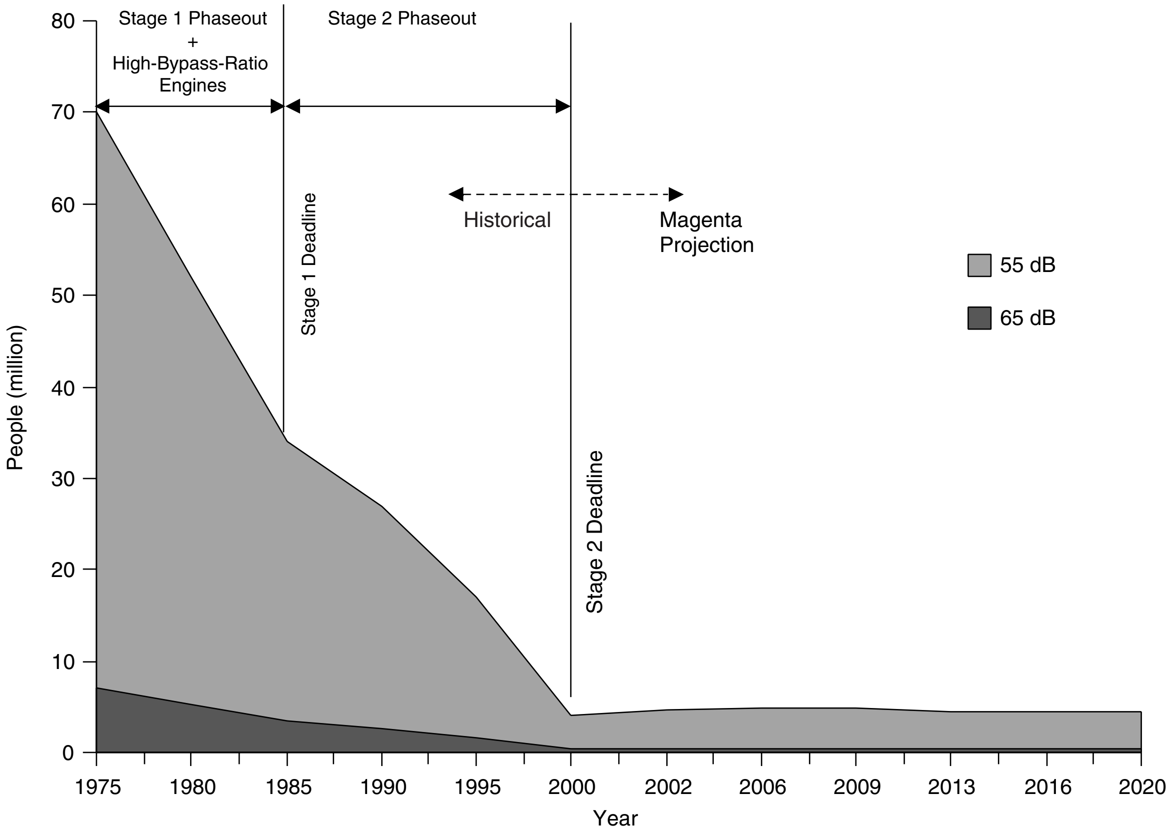

FIGURE 2-3 Estimated trends in number of people affected by aircraft noise in the United States (number of people within 65 dB and 55 dB DNL as a function of time). SOURCE: Lukachko and Waitz, 2001.

Infrequent, unexpected noise can also be more annoying than louder, repetitive jet noise. One municipality near the Atlanta airport has issued legal citations to an airline for nighttime ground testing of engines at high power. The proximity of the testing to residential areas, coupled with the time of night and the abruptness and intensity of the associated noise, contributed to a high level of annoyance. Now, when nighttime testing is required, the airline conducts the tests at a more distant location on the airport property.

As shown in Figure 2-3, the number of people affected by aircraft noise has significantly decreased over the past 25 years. The large reductions in affected population shown in this figure have resulted primarily from three factors:

- improved technology (see Figure 2-1)
- low-noise aircraft operations enabled by advanced aircraft control, navigation, and surveillance technology and advanced air traffic management technology
- mandatory phaseout of old, relatively noisy (Stage 1 and 2) aircraft (see Figure 2-3)

The impact of phasing out noisy aircraft is underscored by Figure 2-3. While the total number of Stage 2 aircraft corresponded to 55 percent of the fleet in 1990, these aircraft contributed to more than 90 percent of the total DNL levels at airports. Notably, the reductions in affected population shown in Figure 2-3 were achieved while the commercial aviation industry provided service to a steadily increasing number of people. An appropriate measure of the mobility provided by the aviation industry is revenue-passenger-kilometers: the number of people moved multiplied by the distance carried. As shown in Figure 2-4, mobility has increased sixfold over the past 30 years and is expected to continue to increase over the next 20 years at a rate of 3 to 5 percent per year.

Estimates by the FAA suggest that further reductions in the number of people in the United States affected by noise will be small over the next 20 years because the current fleet is relatively new and no additional large-scale, mandatory phaseouts of older aircraft are planned. The approximately constant number of people affected results from a balance between projected improvements in technology and projected increases in flight operations.

A simplified representation of the ratio of social costs to social benefits can be estimated by comparing the data on the number of people affected by noise and the amount of travel services provided, as shown in Figures 2-3 and 2-4, respectively. The number of people affected by noise has

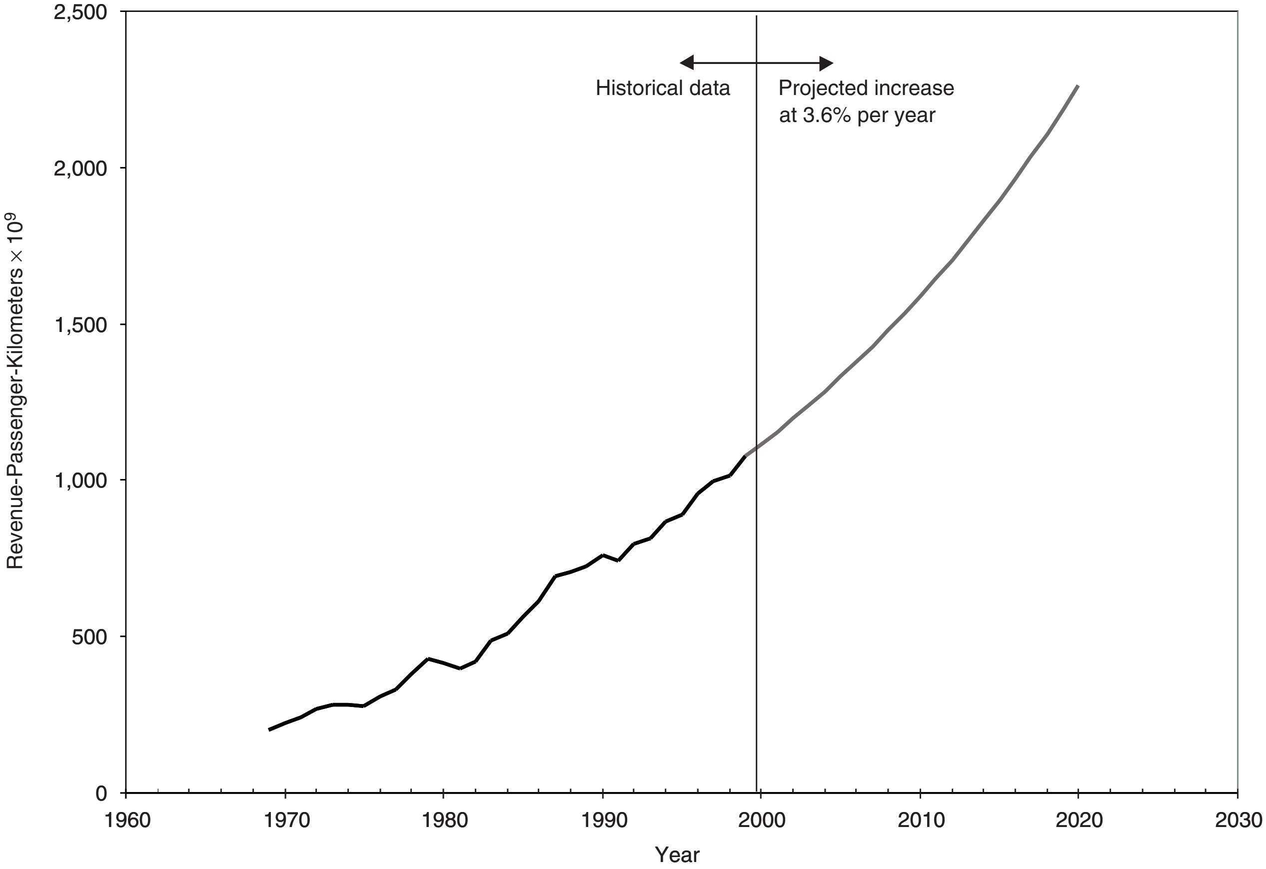

FIGURE 2-4 Historical growth in mobility provided by U.S. commercial aviation. SOURCE: Lukachko and Waitz, 2001.

been reduced by a factor of roughly 15, whereas the amount of travel services provided has increased by a factor of 6. Therefore, the number of affected people per unit of mobility provided has decreased by a factor of nearly 100 over the past 30 years. The foundation of this dramatic reduction has been technological advancements created by both the federal government and private industry. Airports and airlines still view noise as their most urgent environmental issue, however, because of greater public sensitivity to noise and other environmental problems. Increased local awareness of aviation noise causes more airports to impose noise restrictions (see Figure 2-5) and fosters the establishment of more nongovernmental organizations devoted to reducing aviation noise (see Table 2-2).

Most of the federal research and development dollars spent on aviation noise are administered by NASA, with smaller fractions expended by the FAA and the Department of Defense (DoD). Among these organizations, it is primarily NASA's role to carry out research and development. The FAA focuses on assessing noise compatibility, aircraft certification, and regulatory issues, although some development of aircraft noise modeling and assessment tools occurs within the FAA. DoD focuses more directly on issues of noise compatibility around and on military air bases. Typically, NASA's work is intended to conduct basic research and early technology development to enable implementation of new technologies in products by industry. NASA often describes the maturity of technology using its own technology readiness scale. Much of NASA's previous research in aircraft noise was designed to mature technology to a technology readiness level (TRL) of 6, but because of limited funding future research programs (as discussed below) will typically stop at TRL 4 (see Figure 2-6). Depending on a variety of business, regulatory, and technological factors, new technology at TRL 6 can take as long as 15 years to be implemented in commercial aircraft. Technology at TRL 4 takes even longer to be of practical value.

Figure 2-7 shows the federal investments to reduce commercial aviation noise over the past 10 years (in constant year 2000 dollars). The net sum of these expenditures during that time is $440 million. Since the mid-1990s, the overall trend is downward. Under current plans, the level will stabilize at about $20 million per year, less than half of the average annual expenditure for the past 10 years. While definitive financial data are not available on industry expenditures for noise research and related application of this technology, one estimate places the total noise research work by the three major aircraft engine companies (General Electric, Pratt &

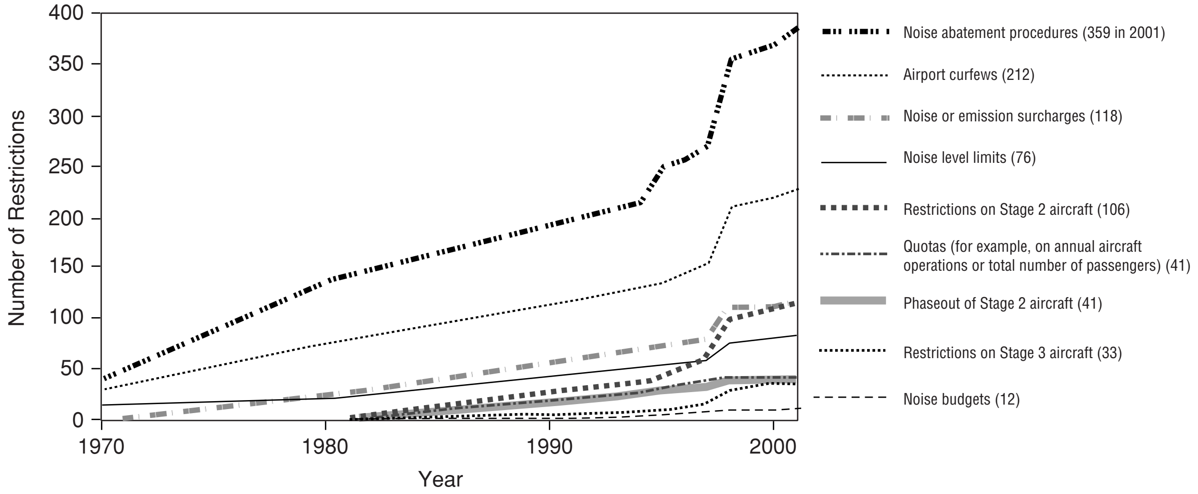

FIGURE 2-5 Trends in aircraft noise regulation: number of airports worldwide imposing various constraints and charges as a function of time. SOURCE: Boeing, 2001.

Whitney, and Rolls-Royce) at between $10 million and $15 million annually. These companies spend additional resources, perhaps on the order of $30 million to $60 million over 2 years, to incorporate noise reduction technology in new engines during product development. Major aircraft companies are estimated to spend a comparable amount of money on noise reduction technologies both for research and development.

It is difficult to make a quantitative statement as to how much of the technological change apparent in Figure 2-1 can be attributed to government expenditures. However, all industry representatives contacted by the committee found NASA research to be critical in advancing aviation noise technology, especially because NASA invests in higher-risk, longer-term research than industry.

FAA noise abatement programs reduce exposure to noise, primarily by soundproofing buildings located near airports and by purchasing land to extend airport property (allowing residents and businesses to relocate elsewhere). Federal noise abatement activities are funded by the Airport Improvement Program and Passenger Facility Charge Program, using money collected from fees and taxes on passenger airline tickets. Money spent on abatement addresses the noise problem one airport at a time, and it can be very costly, with total expenditures for a single airport (from all sources—federal, state, and local governments and the airport authority itself) often amounting to several hundred million dollars. Advances in technology, however, reduce the burden nationally (and globally). Through 2001, $408 million had been spent on sound insulation for residential and school buildings around Chicago's O'Hare International Airport. This is almost as much as the federal government's entire noise technology research and development budget for the past 10 years.

Although federal expenditures on noise research and development have been declining, federal expenditures on noise abatement have been increasing (see Figure 2-8). Perhaps more striking is the small amount spent on research and development compared with that for noise abatement. Over the past 10 years $3.2 billion has been spent on noise abatement—about 7 times more than federal expenditures on noise reduction research and development. The imbalance has been worsening in the past few years (see Figure 2-9). Furthermore, noise abatement cannot fully restore quality of life; soundproofing addresses only interior noise levels, and land purchases displace communities. The most effective—the only—long-term solution is to develop new technology that will lead to quieter aircraft.

Finding 2-1. Growing Cost of Noise. The cost of aviation noise is significant and growing. Aviation noise reduces property values, contributes to delays in expanding airport facilities, and prompts operational restrictions on existing runways that increase congestion, leading to travel delays, high airline capital and operating costs, and high ticket prices.

Finding 2-2. Technology Accomplishments and Goals. Over the past 30 years, the number of people in the United States affected by noise (i.e., the number of people who experience a day-night average sound level of 55 dB) has been reduced by a factor of 15, and the number of people affected by noise per revenue-passenger-kilometer has been reduced by a factor of 100. New technology has contributed significantly to these improvements.

Recommendation 2-1. Balanced Allocation of Funds. Federal expenditures to reduce noise should be reallocated to shift some funds from local abatement, which provides near-term relief for affected communities, to research and tech-

TABLE 2-2 Nongovernmental Organizations Devoted to Reducing Aviation Noise

State	Name of Group
Alabama	Citizens Coalition for Airport Neighbor Rights (CCANR)
Alaska	Cruise Control, Inc.
	Peace and Quiet Coalition
Arizona	Mesa Community Alliance
	Quiet Skies Alliance
	Taxpayers for Responsible Planning
California	Alliance for a New Moffett Field
	Citizens Against Airport Pollution (CAAP)
	Citizens for Safe and Healthy Communities
	Citizens to Silence LAX
	El Toro Airport Info Site
	Move Against Relocating Choppers Here (MARCH)
	No More Noise
	Peninsula Aircraft Noise/Safety Information Committee
	People Over Planes
	Restore Our Airport Rights
	San Francisco Airport Roundtable
	San Lorenzo Citizens Against Airport Noise
	Uproar
Colorado	Alliance to Mitigate Aircraft Noise
	Boulder County Citizens Against Aviation Noise
	Colorado Citizens Against Noise
	Preserve Unique Magnolia Association
District of Columbia	Airport Coordinating Team
	Citizens for Abatement of Aircraft Noise (CAAN)
Florida	Citizens for Control of Airport Noise
	Stop the Boca Raton Airport
Georgia	PDK Watch
Hawaii	Citizens Against Noise of Hawaii
Illinois	Alliance of Residents Concerning O’Hare
Indiana	Save Our Skies
	Victims of Airport Expansion
Kentucky	Airport Neighbors Alliance
Massachusetts	Communities Against Runway Expansion (CARE)
	Community Transportation Alliance of Cape Cod
	Concerned Citizens Coalition
	Safeguarding the Historic Hanscom Area’s Irreplaceable Resources
	United Against MASSPort
Minnesota	Residents Opposed to Airport Racket (ROAR)
	South Metro Airport Action Council (SMAAC)
Missouri	Saint Charles Citizens Against Aircraft Noise
Nevada	Citizens for Airport Accountability
New Jersey	Alliance of Municipalities Concerning Air Traffic
	Branchburg/Readington Airport Coalition (BRAAC)
	New Jersey Coalition Against Aircraft Noise (NJCAAN)
	People Limiting Airport Noise and Expansion (PLANE)
	Quieter Environment Through Sound Thinking (QUEST)
	Runway 22 Coalition
New York	Citizens for Enforcement of MacArthur Airport Control
	Helicopter Noise Coalition of New York City
	Sane Aviation for Everyone (SAFE)
	Ulsterites Fight Overflights
North Carolina	Airport Noise
	Piedmont Quality of Life Coalition
	Raleigh Durham Airport Noise Committee
Ohio	Airport Neighbors Decide
	Akron/Canton Airport Noise
	Citizens Against Reckless Expansion
	Olmsted Falls Airport Committee
Pennsylvania	Bucks Residents for Responsible Airport Management
	Citizens Alliance for Chester County Airport
Rhode Island	Concerned Airport Neighborhoods (CAN)
Tennessee	Airport Area Residents Alliance
Virginia	Citizens Concerned About Jet Noise (CCAJN)
Washington	Airport Communities Coalition (ACC)
	Citizens Against Sea-Tac Expansion
	Citizens Fed-Up with Aviation Noise (CFAN)
	Regional Commission on Airport Affairs
	Seattle Council on Airport Affairs
States with no groups identified	Arkansas, Connecticut, Delaware, Idaho, Iowa, Kansas, Louisiana, Maine, Maryland, Michigan, Mississippi, Montana, Nebraska, New Hampshire, New Mexico, North Dakota, Oklahoma, Oregon, South Carolina, South Dakota, Texas, Utah, Vermont, West Virginia, Wisconsin, Wyoming
National groups	National Helicopter Noise Coalition (NHNC)
	National Organization to Insure a Sound-Controlled Environment (NOISE)
	Rural Alliance for Military Accountability
	U.S.-Citizens Aviation Watch (US-CAW)

SOURCE: Noise Pollution Clearing House, 2002.

nology that will ultimately reduce the total noise produced by aviation. Currently, much more funding is devoted to local abatement than to research and technology. Also, to avoid raising unrealistic expectations, the federal government should realign research goals with funding allocations either by relaxing the goals or, preferably, by reallocating some noise abatement funds to research and technology.

GOVERNMENT GOALS, STRATEGIES, AND POLICIES

In 1997, NASA established noise reduction goals: to reduce the perceived noise of future aircraft by 50 percent in 10 years and 75 percent in 25 years. NASA hoped to achieve these goals by advancing technology to TRL 6 three years prior to the desired date, assuming that would be enough

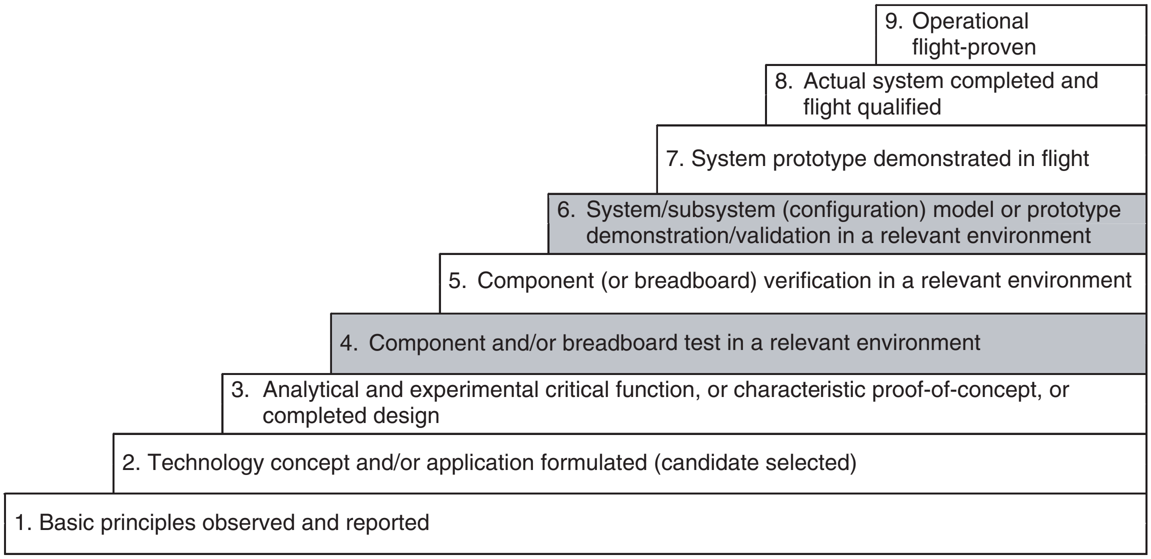

FIGURE 2-6 NASA technology readiness levels. SOURCE: NASA, 2000.

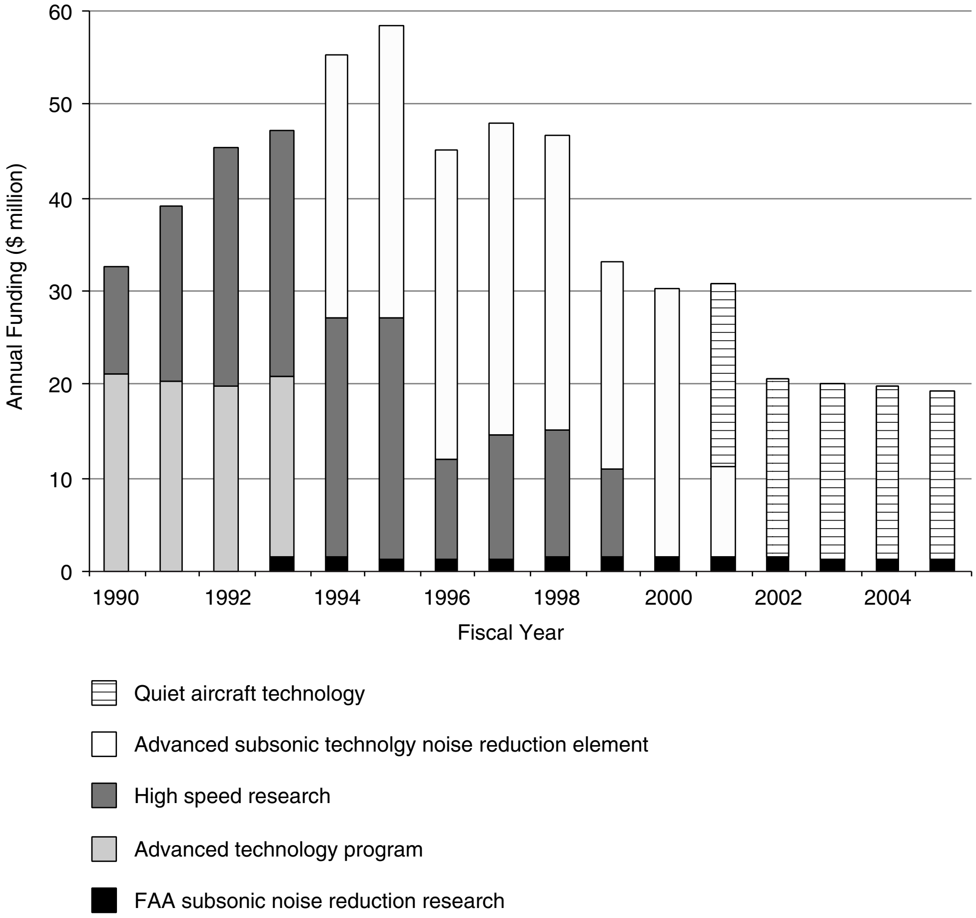

FIGURE 2-7 Federal investments to reduce source noise (in millions of constant year 2000 dollars). SOURCE: Lukachko and Waitz, 2001.

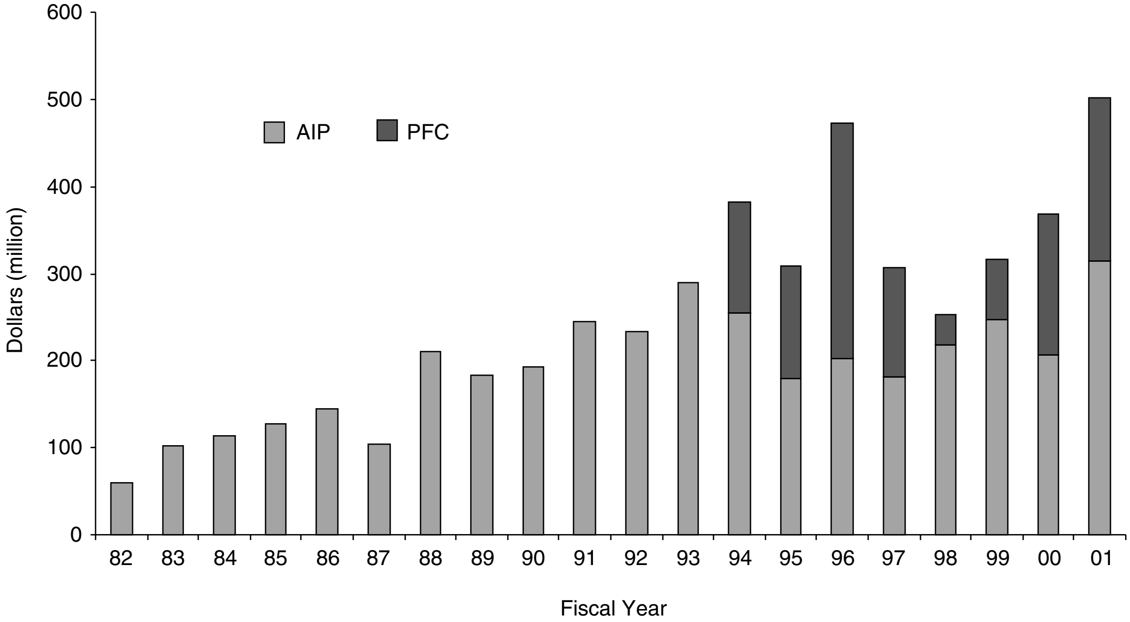

FIGURE 2-8 Federal investments in noise abatement (Airport Improvement Program and Passenger Facility Charge Program expenditures in millions of constant year 2000 dollars). SOURCE: Lukachko and Waitz, 2001.

FIGURE 2-9 Ratio of federal funds spent on local noise abatement projects (soundproofing of homes, etc.) to funds spent by the FAA and NASA on noise research and technology. SOURCE: Lukachko and Waitz, 2001.

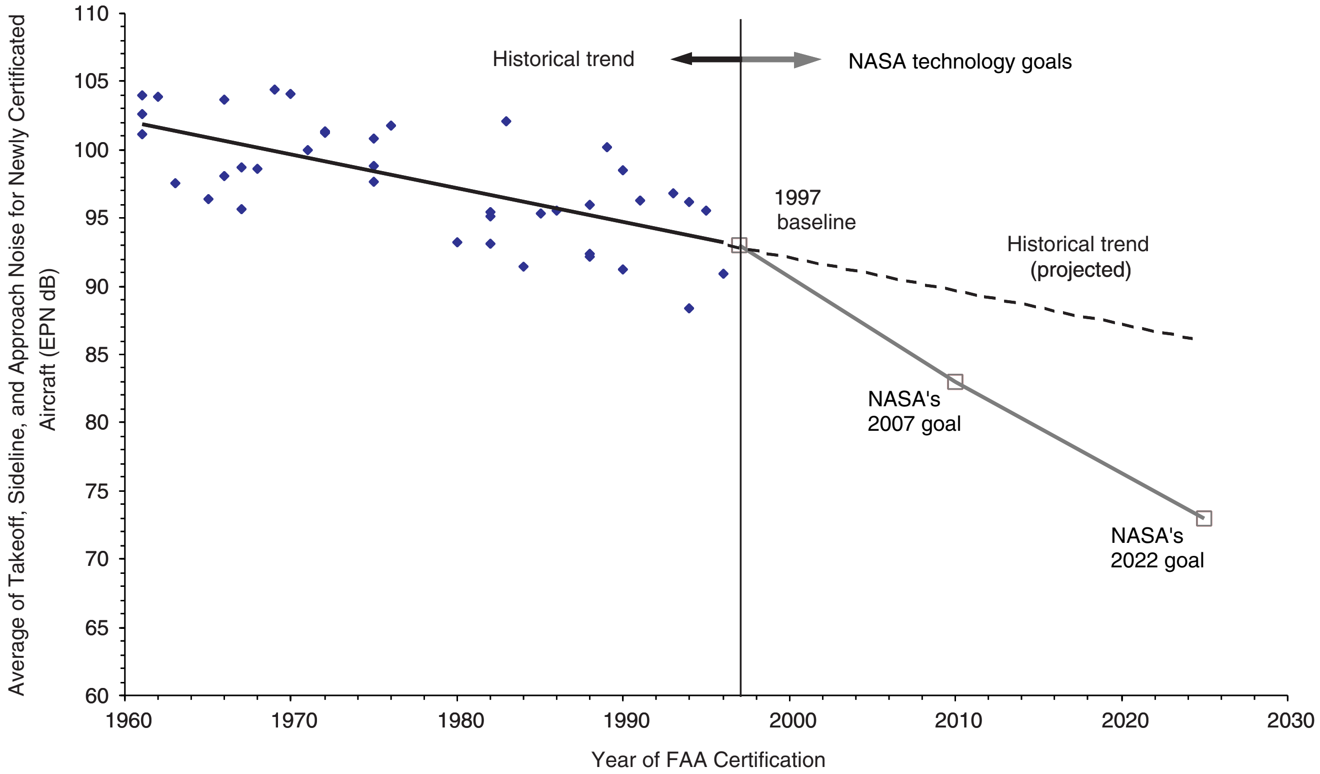

FIGURE 2-10 Historical trends in aircraft noise compared with NASA's noise goals. Centerline takeoff noise for aircraft certificated since 1980 is typically about 4 dB louder than sideline noise during takeoff and about 8 dB louder than approach noise. SOURCE: Lukachko and Waitz, 2001.

time for industry to incorporate the new technology into operational aircraft. Given past history, a 10-year transition period is more realistic. Also, even if new aircraft entering service are quieter, the average noise level is driven by existing aircraft, because they are noisier and more numerous. These older, noisier aircraft may remain in service for 30 years or more. Eventually, however, achieving NASA's technology goals could reduce noise enough at many airports so that a DNL of 55 dB would not be exceeded outside the airport property limits. This level is currently believed by many to be an "acceptable" intrusion into daily life and is consistent with current EPA guidelines for acceptable noise exposure for outdoor activities requisite to protect public health and welfare with a reasonable margin of safety.

The committee believes that the goal of moving the 55 dB DNL contour within the airport boundary is appropriate for federal technology research and development. However, public willingness to accept aviation noise can change, and even achieving this goal does not guarantee that noise will no longer constrain aviation. Also, NASA's goals are so aggressive that they represent a significant change in the rate of technological advancement (see Figure 2-10), a change that is unlikely to occur in an environment of decreasing federal research expenditures (see Figure 2-7). A slower rate of technological advance will provide more time for noise restrictions to grow, creating additional limitations on airports' ability to expand, longer flight delays, and additional expenditures on noise abatement.

Programmatic trends in noise research are illustrated by the fate of NASA's Advanced Subsonic Technology Program. In the noise reduction element of this program, NASA and industry effectively collaborated in accelerating the transition of new technology to commercial products. The program began in 1994 and was on course to achieve its initial noise reduction goals until it was cut short in 2001. NASA had invested about $210 million over 8 years (more than $25 million per year) and produced technology at TRL 5 to 6 that was capable of reducing aviation noise by 8 dB relative to 1992 technology (5 dB relative to 1997 technology). Because of the close collaboration with industry, products employing this technology are already in design, and it is likely that they will be introduced in the market within a few years (i.e., roughly 5 years after the completion of the program).

The Quiet Aircraft Technology (QAT) Program, which replaced the noise-related elements of the Advanced Subsonic Technology Program, has a goal of providing technology to allow a reduction of an additional 5 dB (relative to 1997 technology) at TRL 4 in 5 years. The projected budget is $100 million ($20 million per year). The reduction in the TRL goal (from 6 to 4), a direct result of reduced funding, makes it less likely that innovative research ideas will rapidly transition to industrial implementation.

More than 60 percent of the funds for the QAT Program will be spent within NASA. NASA funding of noise reduction research by industry, which averaged about $14 million per year with the Advanced Subsonic Technology Program, has been reduced to about $5 million per year with the QAT Program. Because these funds are distributed among many companies, the amount of funding provided to any one company may be insufficient to maintain a critical mass of expertise and research and may be insufficient to attract other internal industry research funds. This could significantly reduce the likelihood that new technology will be adopted and implemented in commercial products.

The committee believes that NASA's technical approach to noise reduction research is well balanced, with 45 percent of funds being expended on engine system noise reduction, 30 percent on airframe system noise reduction, and 25 percent on operational measures to reduce aircraft noise and improve noise-impact modeling. NASA based this allocation on a series of aircraft and aviation system studies and six stakeholder meetings and planning workshops conducted over several years with personnel from FAA, industry, universities, and nongovernmental organizations.

The specific objectives of the QAT Program are listed in Table 2-3. Relative to the Advanced Subsonic Technology Program, there has been a shift in the near- versus far-term balance of NASA's noise reduction research. The QAT Program plans to spend about 10 percent of its funds on near-term research, 40 percent on mid-term research, and 50 percent on far-term research, compared with the Advanced Subsonic Technology Program's allocation of 20, 70, and 10 percent for near-, mid-, and far-term research, respectively.

NASA's research is appropriately focused on technology for narrow-body twin-engine aircraft, which will constitute most of the future fleet. However, the fleet composition is changing, with greater reliance on regional jets (see Figure 2-11). The increased use of regional jets is of particular interest because these aircraft will bring jet travel and the associated noise concerns to communities not previously affected. Although regional jets provide only about 4 percent of all revenue-passenger-kilometers, they already account for 40 to 50 percent of all commercial aircraft departures in the United States. Regional jets facilitate the scheduling of more direct flights that bypass hub airports (which could reduce traffic at hub airports), but they also tend to stimulate demand on many routes, including routes to and from hub airports (which increases traffic). In the long term, the increased availability of regional jets will probably result in unexpected changes in noise and emission trends. NASA's limited research portfolio, however, is not well positioned to predict the effects of or respond to changes such as this.

TABLE 2-3 Goal, Objectives, and Approaches for Elements of NASA's Quiet Aircraft Technology Program

Program goal	Develop to TRL 4 those technologies necessary to achieve NASA's 10-year noise reduction goal and identify technologies necessary to achieve the 25-year goal
Objectives	Reduce community noise impact by 5 dB Develop framework to identify technologies for an additional 10 dB reduction Improve source noise models
Challenges	Reduce engine system noise (4 dB) Reduce airframe system noise (4 dB) Enable low-noise operations (2 dB) Improve physics-based source noise prediction Enable real-time impact modeling
Approaches	Component diagnostic laboratory experiments Computational aeroacoustics and fluid dynamics Definition and verification of low-noise operations Air traffic management simulations with controllers and pilots Realistic propagation effects

FAA's noise-related research focuses on system-level noise impact assessment tools, such as the Integrated Noise Model (INM) and the Model for Assessing the Global Exposure to the Noise of Transport Aircraft (MAGENTA). These models are used for noise compatibility planning and for assessing various policy scenarios. The models have considerable leverage: they have guided FAA expenditures of $4.9 billion over the past 20 years as well as $4 billion to $6 billion in capital investment by industry during the 1990s. Unfortunately, the FAA does not have clearly articulated metrics or goals for these models, and thus there is no convenient way to measure the FAA's progress or the appropriateness of its modeling research.

The White House Commission on Aviation Safety and Security recognized the importance of these models, recommending in its final report (1997) that the FAA "develop better quantitative models and analytic techniques to inform management decision making," and urged the FAA "to strengthen its analytic and planning tools, especially through the development of models that give insight into the system-wide consequences of alternative courses of action." Executing these recommendations requires coordination between the FAA (the user and maintainer of the models) and NASA (which provides much of the science that leads to improvements in the models). The principal coordinating body for the two agencies (as well as for the DoD) is the Federal Interagency Committee for Aircraft Noise. The interagency committee facilitates information sharing, but its ability to act as a coordinating body is constrained by the limited authority of its membership. The interagency committee could be stronger and more effective if agencies appointed as rep-

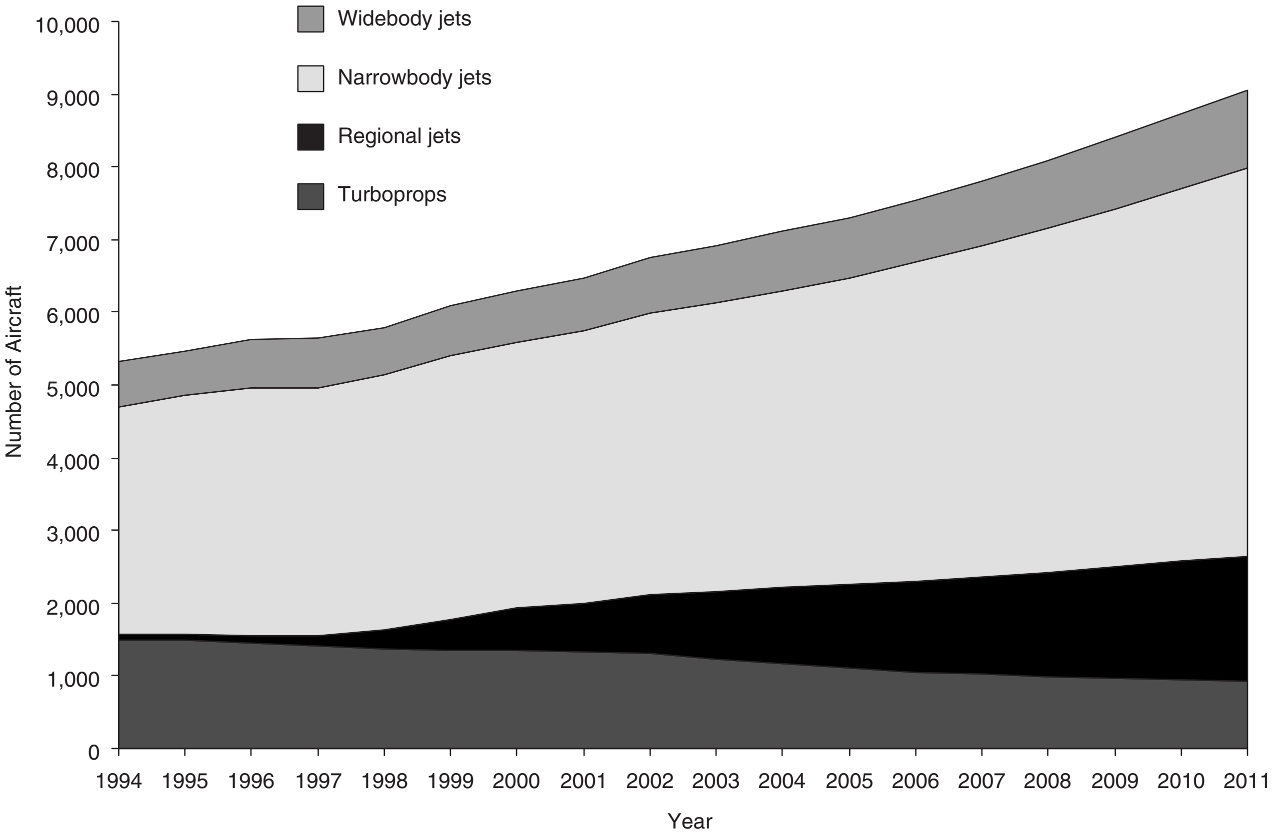

FIGURE 2-11 Changes in the composition of the U.S. commercial fleet, 1994 to 2011. SOURCE: Rolls-Royce, 2001.

resentatives personnel with budgetary authority within their home organizations.

The Committee on Aeronautics Research and Technology for Environmental Compatibility concludes that federal programs and policies for research and technology aimed at addressing aircraft noise are not sufficient to alleviate aircraft noise as a potentially significant barrier to the growth of aviation. While the noise reduction goals of the federal programs for research and technology development are appropriate, the level of technical activity is insufficient to achieve the goals in the planned time periods and it is likely that noise constraints will continue to impede aviation's growth and contributions to the national economy.

Finding 2-3. Achieving Noise Reduction Goals. Additional technological advances now possible could move most objectionable noise within airport boundaries. However, the goal is unlikely to be achieved by NASA's target date of 2022, and achieving the goal may not fully alleviate the constraints that noise places on the aviation industry because of potential changes in the public's perception of the importance of a low-noise environment to quality of life.

Finding 2-4. Major Impediments. The most significant impediments to reducing the impact of aviation noise (or emissions) include long-term growth in the demand for aviation services, long lead times for technology development and adoption, long lifetimes of aircraft in the fleet, high development and capital costs in aerospace, high residual value of the existing fleets, and low levels of research and development funding.

Recommendation 2-2. Technology Maturity and Scope. NASA and other agencies should sustain the most attractive noise reduction research to a technology readiness level high enough (i.e., technology readiness level 6, as defined by NASA) to reduce the technical risk and make it worthwhile for industry to complete development and deploy new technologies in commercial products, even if this occurs at the expense of stopping other research at lower technology readiness levels. NASA and the FAA, in collaboration with other stakeholders (e.g., manufacturers, airlines, airport authorities, local governments, and nongovernmental organizations), should also support research to accomplish the following:

- Establish more clearly the connection between noise and capacity constraints.
- Develop clear metrics for assessing the effectiveness of NASA and FAA noise-modeling efforts.
- Implement a strategic plan for improving noise models based upon the metrics.

- Harmonize U.S. noise reduction research with similar European research.

Recommendation 2-3. Interagency Coordination. Interagency coordination on aircraft noise research should be enhanced by ensuring that the members of the Federal Interagency Committee for Aircraft Noise have budget authority within their own organizations to implement a coordinated strategy for reducing aviation noise.

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3

Emissions

The combustion of hydrocarbon fuels—by aircraft engines as well as other types of internal combustion engines—produces carbon dioxide (CO_2), water vapor, NO_x, carbon monoxide (CO), oxides of sulfur (SO_x), unburned hydrocarbons, particulates (primarily soot, which in high enough concentrations is visible as smoke), and other trace compounds. Aircraft emissions can affect climate, air quality, and ozone on global, regional, and local scales. Emissions can be reduced through improved engines (to create a smaller amount of emissions per pound of thrust), improved aircraft (to reduce the amount of thrust necessary to operate an aircraft with a given passenger and cargo capacity a given distance at a given speed), and improved operational systems and procedures (to use aircraft in a more fuel-efficient manner). NASA has established ambitious goals for reducing two emissions of particular interest: CO_2 and NO_x (see Table 1-4).

Over the years, technical advances in aircraft, engines, and operational systems and procedures have reduced the amount of emissions produced per unit of service provided (i.e., revenue-passenger-kilometer), but these advances have not kept pace with the increased demand for air transportation. Hence, the total amount of emissions from aircraft has increased, but at a rate comparable to emissions produced by other transportation modes and other sectors of the U.S. economy. However, a vigorous research program could increase the rate at which the efficiency of flight improves, provide better information on the significance of aircraft emissions, and help ensure that technical research and new regulatory standards are properly focused.

AIRCRAFT AND ENGINE TECHNOLOGY

Although aircraft fuel consumption is small relative to fuel consumption by other sectors, aircraft emissions are of increasing concern because they are deposited at altitudes where, with the exception of CO_2, they affect the environment differently than ground-based emissions. Emissions from aircraft on or close to the ground are also a concern because, as with emissions from other industrial facilities, they are concentrated in specific localities (i.e., airports) where, over time, local air quality may be degraded.

Commercial aircraft have evolved from the propeller-driven craft of the 1940s and 1950s, through the early jet-powered craft of the 1960s, to contemporary airplanes with high-pressure-ratio engines. During this evolution, airframe aerodynamics and engine performance have been improved, and the weight of aircraft structures and system components has been reduced. These improvements were driven by economic requirements for longer range, higher fuel efficiency, larger capacity, and increased speed, and the net result was an air transportation system with aircraft that are more capable, yet consume less fuel and produce fewer emissions per revenue-passenger-kilometer than ever before. In the past 30 years, approximately 60 percent of the total improvement in fuel efficiency has been attributable to advances in engine technology, with the rest due to improvements in airframe design and more-fuel-efficient operations. Based on past trends, further improvements in engine and airframe efficiency seem likely to reduce fuel consumption per revenue-passenger-kilometer by about 1 percent per year for the next 15 to 20 years. This contrasts with anticipated long-term growth in commercial airline revenue-passenger-kilometers of approximately 3 to 5 percent per year (IPCC, 1999; Lee et al., 2001). In addition, improvements in engine efficiency do not reduce all types of emissions equally. Certification standards for aircraft engines recognize this disparity, allowing high-efficiency engines with high pressure ratios to emit more NO_x than engines of the same size that have lower pressure ratios (and lower efficiency).

NASA has contributed significantly to technological advances in the past, and studies sponsored by NASA's Ultra Efficient Engine Technology Program indicate that future advances could make up much, but not all, of the shortfall between future growth in demand and current projections of technological improvements. New airframe technologies have the potential to reduce current fuel consumption by 25 percent, and new engine technologies could provide an additional improvement of 15 percent over the next 15 years.

Improvements in aircraft fuel efficiency have been similar to fuel-efficiency advances demonstrated by the automobile: in 2000, the average new car used 41 percent less fuel per mile than the average new car in 1973; fuel efficiency of new aircraft (per passenger-seat-kilometer) improved about 34 percent over the same time period.

Additional improvements in aircraft fuel efficiency could be achieved by continued advances in the following areas:

- improvements in airframe aerodynamics from a combination of high-resolution numerical simulations of airflows around aircraft; wind tunnel testing techniques; laminar flow technology; and integrated design of the wing, fuselage, and propulsion system
- reductions in the weight of airframe and engine structures (such as the nacelle, which supports the engine) from lighter and stronger materials, and high-fidelity finite-element models for more accurate analyses of safety and strength load-factor margins
- improvements in the aerodynamics of engine nacelle flows and changes in the shape and length of the engine inlet to reduce local drag effects and increase efficiency
- thrust reversers with higher efficiency to reduce propulsion-system weight
- fly-by-wire and electrical actuation systems to reduce or eliminate the need for heavy hydraulic systems, and fly-by-light systems to replace electrical wiring with lighter-weight fiber optics
- advanced engine technology to increase engine bypass ratio (for lower exhaust jet velocity and higher propulsive efficiency) and to increase engine pressure ratio (for higher thermal efficiency)
- advanced air traffic control and air traffic management systems and procedures to improve operational efficiency—for example, through more direct routing of flights

Even with improvements such as those listed above, most or all new commercial aircraft will not have significantly greater cruise speed, altitude, or range. Large commercial jet aircraft have had cruise speeds of about 500 knots (Mach 0.80 to 0.85) for about 30 years. Typical cruise altitude has also changed little. This trend could change, however, if ongoing Boeing design studies lead to production of a new class of commercial aircraft with cruise speeds of Mach 0.95 or greater. For long-range aircraft, average cruise altitudes have remained fairly constant, at 35,000 to 38,000 feet, over the past 35 years. Although maximum cruise capability has slowly increased and some aircraft can now cruise at altitudes up to approximately 43,000 feet, subsonic aircraft are not expected to see much change in cruise speed or altitude in the foreseeable future. Maximum range is also unlikely to increase significantly, because commercial aircraft can already provide nonstop service between almost any two cities in the world; there is little demand for aircraft with longer ranges.

NASA is the only federal agency with research programs focused on the reduction of emissions from commercial aircraft. NASA's emissions goals, which are focused on CO_2 and NO_x, are commendable, but research funding to achieve these goals has been greatly reduced. Figure 3-1 shows the magnitude of emissions research funded by the High Speed Research (HSR) Program, the Advanced Subsonic Technology Program, and the Ultra Efficient Engine Technology Program.

A major thrust of the HSR Program was to develop low-NO_x combustor technology for future supersonic aircraft. Component tests demonstrated a reduction of 80 to 90 percent, achieving an NO_x emission index of 5 grams per kilogram of fuel (which was the program goal). However, the HSR Program was canceled before the low-NO_x technology could be integrated in a test engine to characterize transitory and steady-state performance and demonstrate programmatic goals such as low noise and long life. NASA also conducted extensive combustor emissions research under the Advanced Subsonic Technology Program before it was terminated and replaced with the Ultra Efficient Engine Technology Program. The goals of the latter program are to reduce NO_x by 70 percent (with hardware demonstrations at TRL 5) and to reduce CO_2 emissions by 15 percent (with hardware demonstrations at TRL 4). Figure 3-2 shows how funds from all three programs have been allocated.

As with any carbon-based fuel, the major combustion products of conventional jet fuel are CO_2 and water vapor. Reducing the emission of CO_2 and water requires either reduced fuel consumption (through the development of more efficient engines, aircraft, and operational systems and procedures, as discussed above) or the use of alternative fuels. Even though contemporary commercial jet aircraft are designed to operate exclusively with aviation kerosene as a fuel, gas turbine engines can operate with a wide variety of liquid and gaseous fuels. In fact, derivatives of several operational aircraft engines are used in marine and industrial applications using natural gas, diesel fuel, alcohol, and many other fuels. Current and future aircraft engines could also be configured to operate with alternative fuels, such as natural gas or hydrogen. Natural gas would reduce CO_2 emissions on the order of 20 percent relative to kerosene. With hydrogen, zero CO_2 emissions would result. However, both fuels, especially hydrogen, would increase emissions of water vapor.

Because aircraft have limited volumes available to store fuel, natural gas or hydrogen would have to be in liquefied form. Although the energy density of hydrogen by weight is nearly three times that of conventional aviation fuels, the energy density by volume is one-fourth that of conventional

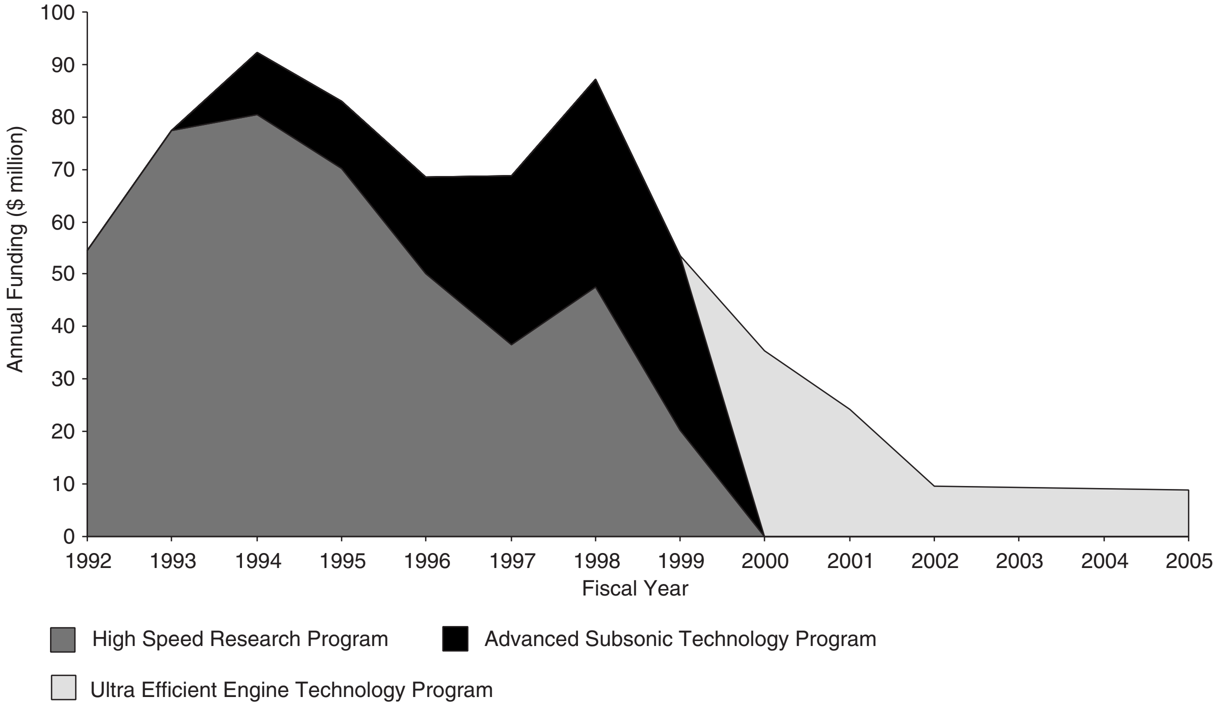

FIGURE 3-1 Funding for emissions research (adjusted to constant year 2000 dollars).

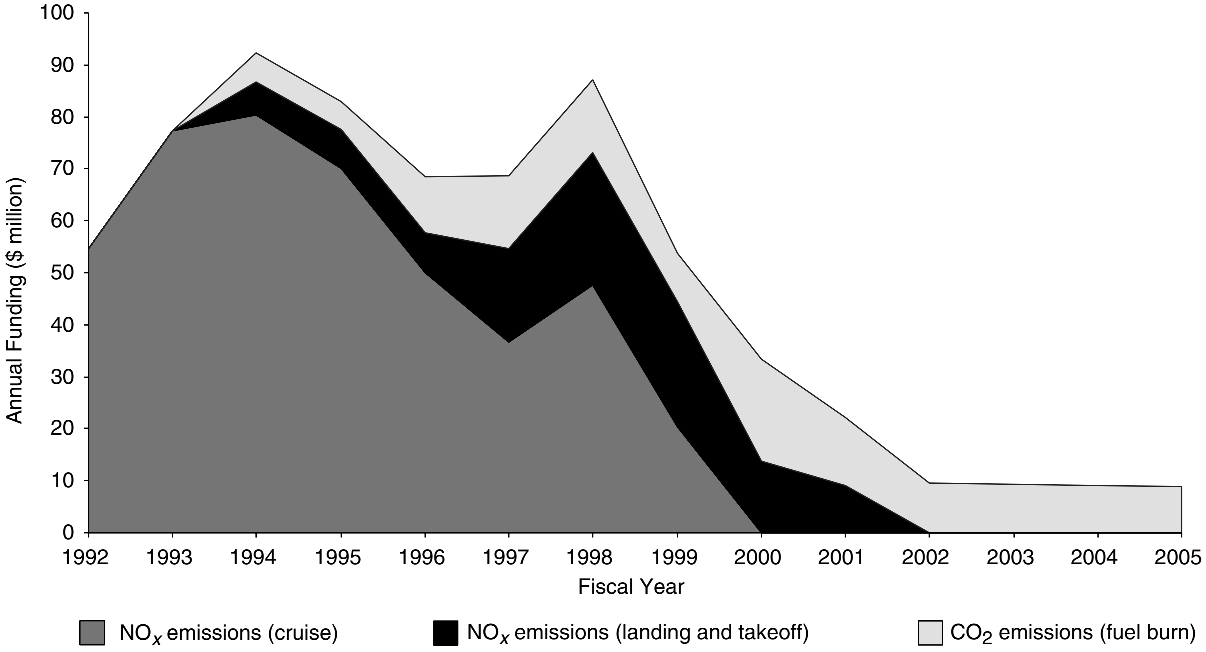

FIGURE 3-2 Allocations of NASA's emissions research funding (adjusted to constant year 2000 dollars).

aviation fuels. In addition, the potential weight savings of hydrogen fuel is offset by the additional weight of the liquid cryogenic fuel storage and handling systems and associated aircraft structures. The engineering challenges associated with accommodating low-density, cryogenic fuels in aircraft fuel tankage and supply systems are so substantial that their use can probably only be considered in new aircraft specifically designed for such fuels. Other major impediments, especially with respect to hydrogen, include cost, availability, and infrastructure (for production, transportation, storage, and aircraft servicing). Natural gas is readily available, but hydrogen must be produced. One approach for producing hydrogen would be to release and collect hydrogen from hydrocarbon fuels, but that process releases 2 to 4 times more CO_2 than simply using hydrocarbon fuels directly as an aircraft fuel.

Another alternative for producing hydrogen would be electrolysis of water, but that assumes the availability of large amounts of electricity not produced by power plants powered by fossil fuels. Burning hydrocarbon fuels to produce electricity to produce hydrogen to replace the use of hydrocarbons as a jet fuel would release more CO_2 than continuing to use conventional hydrocarbon jet fuel. Given the magnitude of these challenges and the long time it would take to develop and deploy significant numbers of new commercial aircraft equipped to operate with alternative fuels, it seems highly likely that commercial aviation will be dominated by aircraft powered by conventional jet fuels for the foreseeable future.

Finding 3-1. Gap Between Technology and Demand. Continuation of ongoing technology research will reduce fuel consumption per revenue-passenger-kilometer by about 1 percent per year over the next 15 to 20 years. During the same time, the demand for air transportation services is expected to increase by 3 to 5 percent per year. An aggressive, broad-based technology program that encompasses propulsion systems, the airframe, and operational systems and procedures could significantly close this gap. Existing allocations of research funding and funding trends within NASA and the FAA do not support such a program.

Finding 3-2. Gap Between NASA Goals and Programs. NASA funding to achieve its goals for reducing CO_2 and NO_x emissions is insufficient to reach the specified milestones on time. Little or no funding is available for research related to other emissions, such as hydrocarbons, particulates, and aerosols, which may also have significant effects on the atmosphere locally, regionally, or globally.

ATMOSPHERIC ASPECTS

Aircraft emissions can affect the atmosphere on global, regional, and local scales. Aircraft emissions include primary emissions (that are present in the engine exhaust as it leaves the aircraft) and secondary emissions (that are produced in the atmosphere by chemical reactions that use the primary emissions either as a reactant or a catalyst). The primary emissions of greatest concern are CO_2, water vapor, NO_x, particulates (primarily soot), and SO_x. Primary emissions of less concern include CO and unburned hydrocarbons. Secondary emissions include aerosols and some types of particulates. Typical levels of primary emissions are shown in Table 3-1.

Global Effects

Globally, the major concerns with aircraft emissions are (1) the potential for subsonic aircraft operating in the upper troposphere to contribute to climate change and (2) the effects of aircraft operations in the troposphere and stratosphere in altering the concentration of ozone (see Table 3-2).

TABLE 3-1 Typical Aircraft Turbine Engine Exhaust Gas Composition at Cruise Operating Conditions

			Concentration	
	Constituent	Emission Index (g/kg fuel)	(vol-%)	(ppm)
Combustion products	CO_2	3,200	4.1	
	Water	1,200	3.7	
Pollutants	NO_x as NO_2	15		190
	CO	1		20
	SO_x	1		9
	HC (as CH_4)	0.20		7
	Soot (as C)	0.02		1

Note: For Jet A fuel ($C_nH_{1.8n}$) and an overall fuel/air ratio of 0.020.

TABLE 3-2 Global, Regional, and Local Effects of Aircraft Emissions

Constituent	Global Effects	Regional Effects	Local Effects
Carbon Dioxide (CO_2) CO_2 is a greenhouse gas that, like water vapor, is an unavoidable by-product of the combustion of fossil fuels. When the concentration of CO_2 in the atmosphere changes, the time to reach equilibration ranges from about 5 years (with respect to the biosphere and surface layers of the ocean) to hundreds of years (with respect to the full ocean).	The relative importance of CO_2 produced by aviation is equal to the amount of fossil fuel used by aviation compared with that consumed for other uses. In spite of the enormous gains made in the fuel efficiency of aircraft, total fuel consumption by U.S. commercial aviation continues to increase, but at a rate comparable with overall U.S. growth in the use of petroleum and other fossil fuels.	None	None
Water Vapor, Contrails, and Cirrus Clouds Water vapor is a greenhouse gas, but the vast majority of water vapor in the atmosphere comes from evaporation of water. The emission of water vapor from aircraft is not significant except, perhaps, in the upper troposphere or lower stratosphere, where it can lead to the formation of contrails and cirrus clouds.	The effect of aviation-induced cirrus clouds is highly uncertain. They may have very little or no effect, or they may affect the global radiation budget more than CO_2. The effect may also vary with latitude and season. More research is needed to adequately understand the effects of contrails and aviation-induced cirrus clouds and to determine if technology goals and programs should be established to mitigate their environmental impacts.	Even if the effects of contrails and aviation-induced cirrus clouds are small when averaged globally, they may have significant climatological effects in some regions.	None
Oxides of Nitrogen (NO_x) Nitric oxide (NO) and nitrogen dioxide (NO_2) together are referred to as NO_x. Both are generated by high temperatures in jet engines, primarily in the combustor. Nitrogen in jet fuel will contribute to the formation of NO_x, but most NO_x is formed from nitrogen and oxygen in the air. The highest levels of NO_x are produced at the highest engine power settings, and the most practical approach for reducing NO_x is to reduce flame temperatures at high power conditions. This can be accomplished using complex, staged combustors or combustors with variable geometry that provide good performance at both high and low power settings. Low-NO_x combustor technology developed by NASA and industry is now adequate to satisfy current regulatory standards. In fact, some advanced combustors can reduce NO_x as much as 60 percent below the ICAO standard, but they currently have a limited market because (1) they cost more and weigh more than simpler combustors (that reduce NO_x to about 35 percent below current standards) and (2) they provide no economic benefits to offset the higher cost and weight.	NO_x emissions in the upper troposphere increase the amount of ozone (by roughly 6 percent in 1992). This increase may have *decreased* UV radiation at the Earth's surface by 1 percent at 45 degrees latitude, and growth in aviation could double the effect by 2050. However, NO_x emissions in the stratosphere (which can occur with some flights during winter or at high latitudes) can reduce ozone, although the net effect of subsonic aircraft is uncertain. Assessing the effect of aircraft NO_x on ozone is complex because NO_x has a short lifetime (days to weeks), high variability, and many sources other than aviation, including lightning and mixing from lower levels of the atmosphere. Additional laboratory tests, field observations of aircraft emissions, and detailed studies of the chemistry involved in ozone production are needed to develop a better understanding.	NO_x emissions can also produce regional variations in ozone—ozone resulting from aircraft emissions of NO_x is concentrated in the Northern Hemisphere and along major flight routes.	NO_x is a local concern because it contributes to the formation of photochemical smog and/or ozone in the lower atmosphere. A few major European airports have implemented landing fees that reward operators who use ultralow-NO_x combustors while penalizing operators using standard combustors. The cost differential does not appear to be a sufficient financial incentive to most international air carriers, for which operations at these airports represent a very small fraction of their total operations.

Particulates and Aerosols Solid particulates in aircraft exhaust generally consist of carbon, sulfates, and metals. The most prevalent particulates are carbon particles (soot), which cause visible smoke if the concentration is high enough. Soot is caused by locally rich fuel-air mixtures within the combustor primary zone and, to a lesser extent, by high combustor operating pressures. The turbine breaks up some large soot particles, while some small particles agglomerate in the exhaust plume to form larger particles The highest level of soot typically occurs during takeoff and climbout when fuel flows and pressures are at their highest. As the atmosphere cools aircraft exhaust, particulates, water vapor, and other constituents in the exhaust of hydrocarbon-fueled engines can form liquid aerosols, which consist of a colloidal suspension of liquid particles in a gas. (Fog is an example of a liquid aerosol.)	The atmospheric effects of soot and other particulates are uncertain—the effects of soot have been determined to only within a factor of 2—and may be important. Particulates provide nuclei for the formation of liquid droplets in the atmosphere and may be involved in the formation of contrails. Soot absorbs and, to a lesser extent, scatters incoming solar radiation. If soot particles are absorbed by aerosol droplets, soot absorbs more solar radiation, which could contribute to climate change. Soot also has the potential to alter the abundance of atmospheric trace constituents by facilitating chemical reactions that would not otherwise be possible.	Particulates and aerosols can contribute to changes in atmospheric visibility and ozone on a regional scale, but this has not been observed as a significant problem with regard to aircraft emissions.	Visible smoke emissions are highly objectionable, especially in and around airports, but low-smoke combustors were incorporated into operational engines beginning more than 30 years ago, and visible smoke is no longer an issue. Particulates, however, may contribute to the formation of photochemical smog and may be a health hazard. While solid carbon is relatively inert, it tends to absorb unburned hydrocarbons, which are potentially carcinogenic and might be absorbed in the lungs. Some particulates might also be able to block some air passages in the lungs. In addition, aerosol droplets can contain combustion by-products in a much more concentrated form than the exhaust gases from which they are formed, which may pose a health risk if they are ingested into the lungs and absorbed into the body. Available research is inadequate to assess the validity of these health concerns. Recent speculation about community health problems in the vicinity of airports suggests that further research may be warranted. However, health problems associated with particulates and aerosols (to the extent that there is a problem) would not be unique to emissions from aircraft, and corrective action, if required, should address other regional and local sources of particulates and aerosols, such as automobiles.
Oxides of Sulfur (SO_x) SO_x is generated in the combustor from sulfur in the fuel. Aircraft generally produce very little SO_x because the sulfur content of aviation fuels is low—generally well below the regulatory limit. However, SO_x emissions even in minute quantities may increase the level of particulates and aerosols. The processes by which these particulates and aerosols are formed is not well understood, and their ultimate significance in terms of atmospheric effects is uncertain.			

(continued)

TABLE 3-2 Continued

Constituent	Global Effects	Regional Effects	Local Effects
Carbon Monoxide (CO) CO emissions are the result of incomplete combustion and are produced primarily at taxi and engine idle conditions on the ground. At higher engine power settings the combustor operates with essentially 100 percent combustion efficiency, effectively eliminating the production of CO. Between 1975 and 1985, combustor designs were modified to improve combustion efficiencies at low power conditions. Today, almost all modern engines have CO emissions that are well below the regulatory limits.	CO results in higher concentrations of ozone and methane and thus acts as an indirect greenhouse gas, but the CO in aircraft emissions is a very small fraction of all anthropogenic CO.	None	Early investigations showed low levels of CO near airport terminals, with ground support vehicles being the major contributor. Subsequent improvements in the combustion efficiency of aircraft and ground support vehicles have essentially eliminated CO as a concern.
Unburned Hydrocarbons (HCs) Emissions of unburned HC are composed of many components. Although present in only trace quantities, some components are classified as hazardous air pollutants (see below). Like CO, HC emissions are caused by incomplete combustion and have been reduced by the same improvements in engine design that have reduced CO emissions. Airborne HC may also result from vaporization of liquid fuel from spills, venting of fuel tanks, or engine startup.	The global effects of HC emissions are similar to those of CO, and their effects are estimated to be negligible.	Unburned HCs are a precursor to photochemical smog and/or ozone. However, unburned HCs are also created by other users of hydrocarbon fuels. The extent to which unburned HCs from aircraft pose a particular problem regionally or locally is uncertain.	
Hazardous Air Pollutants The EPA defines hazardous air pollutants (also referred to as toxic air pollutants) as pollutants that are known or suspected to cause cancer or other serious health effects, such as birth defects, or adverse environmental effects. One study that analyzed the exhaust from two jet engines (one an older design, one a newer design) detected benzene, formaldehyde, and several other chemicals that appear on the EPA's list of hazardous air pollutants (Spicer et al., 1984). The measurements were made at idle power in order to obtain measurable amounts—at higher power levels the chemicals were not produced in easily measurable concentrations. Also, the measurements were taken in the exhaust stream and therefore did not include any dilution or any subsequent chemical reactions that may take place. The emission levels detected were typical of the emissions produced by other types of engines that use hydrocarbon fuels. The pollutants in the exhaust of the newer engine were approximately half the levels of the older engine, with the exception of formaldehyde (which was about the same). Better data is needed to assess what effects, if any, may result from emissions of hazardous air pollutants by the current fleet of commercial aircraft.			

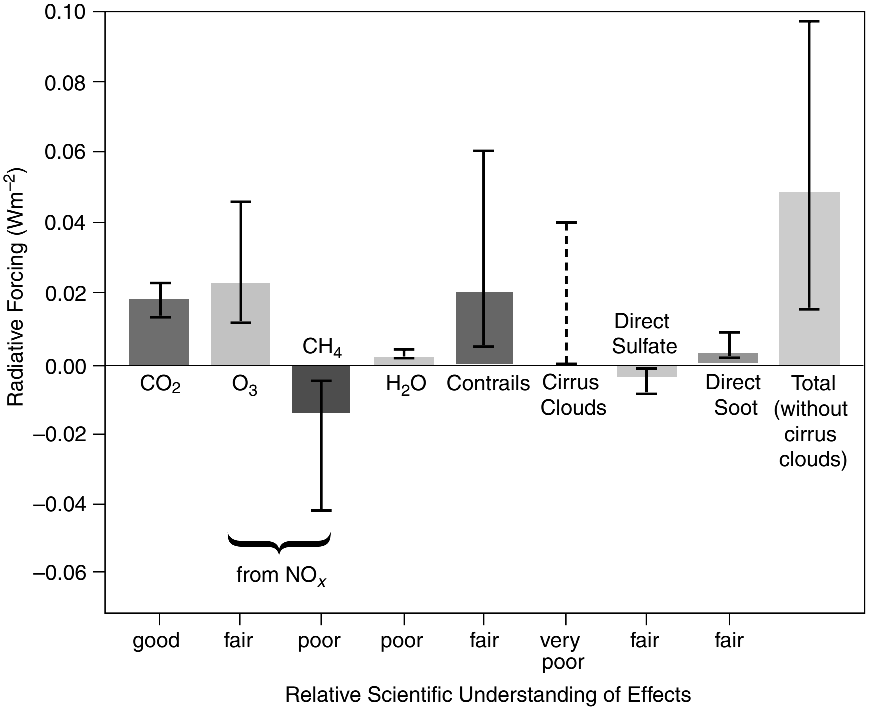

FIGURE 3-3 Radiative forcing caused by the global fleet of commercial subsonic aircraft as of 1992. The vertical line embedded in each bar depicts a two-thirds uncertainty range, meaning that there is one chance in three that the true value falls outside the ranges shown. Available information on cirrus clouds was judged to be insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The adjectives below each bar are relative appraisals of the level of scientific understanding associated with each component. SOURCE: IPCC, 1999.

Ozone directly affects the level of ultraviolet (UV) radiation reaching the Earth's surface and, through photochemical reactions, alters the abundance of reactive gases in the atmosphere, such as methane. The net effect of aircraft emissions on climate change is shown in Figure 3-3. (An increase in radiative forcing tends to cause higher temperatures.) Aviation accounts for perhaps 3.5 percent of anthropogenic changes to radiative forcing and is expected to account for about 5 percent in 2050. Beneficial effects are also possible, however, in the form of reduced exposure to UV radiation caused by higher levels of ozone in the troposphere (which result from the emission of NO_x). In any case, estimates of the future impact of aviation are imprecise because of uncertainties about (1) the total amount of emissions that commercial aviation will produce in the future and (2) the accuracy of current methods for quantifying the impact of aviation emissions. The latter uncertainty is reflected in the range of uncertainty shown for each of the emissions in Figure 3-3. Reducing these uncertainties is important to ensure that technology programs are properly directed. In particular, NASA's environmental goals are focused on reducing CO_2 and NO_x, but, as shown by Figure 3-3, contrails and cirrus clouds could affect climate change as much or more than CO_2 and NO_x emissions.

Regional Effects

On a regional scale the emissions of potential interest are water vapor, NO_x, particulates, and aerosols. However, little effort has been made to assess regional effects, and available data are insufficient to estimate either the current or future effects of aircraft. Whatever effects do or will exist, however, are an extension of either global or local effects, and efforts made to reduce those effects should also mitigate regional effects. Nonetheless, additional research is needed to determine if those efforts will ensure that regions with large amounts of air traffic (such as the northeastern United States or Western Europe) will not experience unacceptable changes to the environment either at the surface or at higher altitudes.

Local Effects

At the local level, aircraft emissions have been a concern for about 30 years—since the use of gas turbine engines in commercial service first became widespread. Federal regulations to limit the effects of aircraft on local air quality were first issued in 1973 by the FAA and EPA. These regulations required the use of low-smoke combustors, prohibited the intentional venting of fuel from the engine manifold after normal shutdown, and described prospective standards for virtually all pollutants; with some modifications, those standards would ultimately appear in regulations issued in 1983. Also in the early 1980s, ICAO developed similar standards and recommended practices to protect local air quality in the vicinity of airports. Since 1997, airport construction projects that require FAA approval or support have had to show that all emissions resulting from the project, both directly and indirectly, would be consistent with state implementation plans for meeting federal air quality standards. As a result, localities and regions with chronic air quality problems would especially benefit from the availability and use of technology that increases fuel efficiency and reduces aircraft emissions.

Current needs also include better understanding of the health concerns, if any, posed by aircraft emissions of hazardous air pollutants (Ozone Transport Committee, 2001 and Holzman, 1997). Very few data exist for characterizing aircraft exhaust with regard to hazardous air pollutants, many of which are mutagenic and carcinogenic, or for comparing the possible effects of aircraft exhaust with those of other potential sources of hazardous air pollutants, such as automobiles. Although hazardous air pollutants are present in aircraft emissions only in small concentrations, environmental challenges that cite these emissions may be hard to deflect without better data.

Atmospheric Research

Two decades of research have demonstrated the importance of laboratory studies, field observations, and numerical modeling for understanding the effects of aircraft emissions on global climate issues. The federal government continues to support several small research programs, such as NASA's Atmospheric Effects of Aviation Project, but funding for this effort has been reduced from about $12 million to about $4 million per year. NASA has a stratospheric chemistry program, which studies some aspects of tropospheric chemistry that are important for understanding the stratosphere. NASA also has a tropospheric chemistry program, which is funded at about $4 million per year, but the focus is on the mid- and free troposphere, which encompass altitudes below the region of primary interest to commercial aviation. The Department of Energy's Atmospheric Radiation Measurement Program studies the effects of aerosols on climate and has provided some information relevant to aviation, but it is not focused on aerosols of particular interest to aviation. The Atmospheric Chemistry Program of the National Science Foundation funds some basic studies of atmospheric and chemical processes that will help assess the effects of aviation.

Recommendation 3-1. Research on Global, Regional, and Local Emissions. NASA should continue to take the lead in supporting federal research to investigate the relationships among aircraft emissions (CO_2, water vapor, NO_x, SO_x, aerosols, particulates, unburned hydrocarbons, and other hazardous air pollutants) in the stratosphere, troposphere, and near the ground, and the resulting changes in cirrus clouds, ozone, climate, and air quality (globally, regionally, and locally, as appropriate). Other agencies interested in aircraft or the environment should also support basic research related to these programmatic goals.

Recommendation 3-2. Eliminating Uncertainties. NASA should support additional research on the environmental effects of aviation to ensure that technology goals are appropriate and to validate that regulatory standards will effectively limit potential environmental and public health effects of aircraft emissions, while eliminating uncertainties that could lead to unnecessarily strict regulations.

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4

Environmental Costs and Benefits

Government-sponsored research and technology programs can provide a solid foundation for defining realistic environmental goals and for the development of environmental policies and regulations to meet such goals. To ensure that the goals and policies for aviation are appropriate, the full extent of environmental costs, the economic benefits of reducing noise and emissions, and the potential of financial incentives to reduce environmental impacts should all be considered.

INCENTIVES

Aircraft and engine manufacturers respond to the aircraft operator and transportation markets they serve. Over the past 20 years, these markets have become less regulated in terms of business activities and more competitive throughout the world. More than ever, manufacturers are called upon to produce aircraft that cost less and are more reliable than their predecessors. At the same time, government intervention is important to encourage manufacturers, operators, and consumers[1] to reduce the environmental consequences of aircraft operations. In fact, in competitive markets, aggressive action to address costly environmental problems unilaterally can place an operator at a disadvantage relative to its competitors. This situation is not unique to aviation.

At least since the founding of the National Advisory Committee for Aeronautics (NASA's predecessor) in 1915, the U.S. government has accepted a role in addressing the environmental consequences of aviation and has developed two approaches for meeting its responsibility. First, it assists the private sector in developing technologies to address the environmental consequences of aviation, and, second, it uses regulations to mandate reductions in noise and emissions, typically through the use of advanced technology made available by the first approach.

The ultimate issue for government in this arena is to decide how and when to use its legislative and regulatory powers to intervene in the market. People and groups who object to the effects of airports on the environment attempt to harness these powers through political action and litigation. One important lever is the process for issuing permits for airport expansions, by which airport expansions may be delayed, reduced in scope, canceled, or modified to include environmental remediation programs. Other tactics include supporting more stringent certification standards for engines and aircraft, establishing new operating restrictions at airports, and opposing the conversion of decommissioned military airports to civilian use. Such efforts reflect both real and perceived problems in local communities and the environment. They impose real costs on operators, manufacturers, airports, and, ultimately, consumers of aviation services, and they sometimes prompt local, state, national, and international government organizations to take action. However, they often involve expensive, lengthy adversarial processes in which both environmental advocates and aviation interests expend a great deal of resources to manage the process, rather than taking direct action to reduce environmental impacts.

Another, nonadversarial approach to reducing the environmental impacts of aviation would be the creation of financial incentives for industry to do more than regulatory standards require. Such incentives would encourage industry to manufacture and operate cleaner and quieter aircraft without waiting for the next round of more stringent environmental regulations. These incentives would also encourage industry to fund the development of environmental technology, thereby leveraging government research funds. Without such incentives, industry will continue to respond to normal business incentives and consumer priorities, which can provide disincentives to invest in advanced environmental technology. For example, airlines currently have a diffi-

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[1] In this report "consumer" includes travelers and all others who benefit from a robust air transportation system.

cult time justifying the expense of optional engine equipment to reduce emissions if standard, lower-cost engine configurations already meet regulatory requirements. If low-emission engines cost more and provide no additional benefits other than low emissions, they make it harder to satisfy the consumer's desire for low fares.

Establishing appropriate financial incentives can be difficult, because government officials cannot easily predict the effects of proposed interventions, especially when they depart from the traditional regulatory approach. Possibilities include the following:

- adjusting operational costs (such as landing fees, fuel taxes, or fees for air traffic control services) to provide financial incentives to improve system operational efficiency by shifting flights from peak hours and congested airports to off-peak hours and less congested airports (incentives would have to be passed on to consumers through changes in ticket prices to alter consumer behavior in a way that would allow airlines to compete effectively with an altered schedule)
- adjusting landing fees according to the amount of emissions or noise produced by each aircraft

A few airports in Europe are already using the latter approach, but it would be more effective if implemented through international authorities to avoid a patchwork of unpredictable requirements with inconsistent goals. Also, financial incentives should be administered in a revenue-neutral way (i.e., higher fees for some aircraft operations should be offset by lower fees for other aircraft operations) to avoid using environmental concerns simply as a means to raise taxes.

COSTS OF NOISE AND EMISSIONS

Aviation policy should satisfy national environmental goals and the public's demand for aviation services. Government policies could be improved if decision makers had a more comprehensive understanding of the societal benefits and costs associated with air transportation, especially with regard to nonmarket factors such as congestion, noise, and emissions. This knowledge would aid in establishing policies (with regard to research, regulations, and financial incentives) that allow consumers, operators, and manufacturers to make individual decisions consistent with government interests in maximizing overall benefits and reducing overall costs.

Economic efficiency is already used both in the ICAO's Committee on Aviation Environmental Protection and in the FAA's own rulemaking process, which calls for cost-benefit analyses of proposals to issue new or amended regulations, expand airports, or modify airport operating restrictions. For example, Part 161.305 of the Federal Aviation Regulations requires that airport operators proposing aircraft operating restrictions provide evidence that "other available remedies are infeasible or would be less cost-effective" than the policy being proposed.

Economic Costs of Noise

As discussed in Chapter 2, community resistance to noise begins somewhere between 55 and 65 dB DNL, with the higher level being the current definition for noise-affected populations applied by both the FAA and the Department of Housing and Urban Development and the lower level suggested by the EPA.

Existing research has investigated the economic consequences of noise exposure in communities empirically. Several studies have examined the impact of noise on property value, concluding that home prices drop about 0.6 percent per dB of DNL exposure (Schipper et al., 1998). Many of these studies are 20 years old, however, and need to be updated to determine if the tolerance for noise has changed.

In addition to property value, another measure of the cost of noise is the willingness of property owners to accept the noise in exchange for payment. Knowing what people would be willing to accept to be exposed to different levels of noise could form the basis for making periodic payments for noise easements (for example, in the form of reduced property taxes). The cost-effectiveness of such payments could be compared with other tools used to address community resistance to noise (i.e., airport operating restrictions, regulations, the purchase of property in noise-affected communities, zoning land for uses compatible with the level of noise, and NASA research and technology programs).

Although the acceptability of noise varies from place to place, the aircraft that produce the noise must be accepted everyplace they fly. In the United States, airport noise regulations are the sole province of the federal government. In accordance with Part 161 of the Federal Aviation Regulations, airports and state and local governments may impose new aircraft noise and access restrictions only after demonstrating to the FAA that less-costly alternatives are not available. Since this requirement was established in the early 1990s, no airport or state or local government has met the requirements of Part 161 to impose new restrictions. Noise exposure dropped dramatically during the 1990s in any case, because of the concurrent decision to lower noise standards and phase out older, noisier (Stage 2) aircraft that could not meet the new standards.

Economic Costs of Local Emissions

The Clean Air Act and FAA certification regulations (Federal Aviation Regulations, Part 34) regulate allowable levels of emissions. When an airport is located in a nonattainment area (i.e., an area that does not meet federally mandated air quality levels), airport expansions can be delayed until local air quality is in compliance. EPA standards are based on the health effects and, ultimately, the economic effects of emissions. Studies provide a wealth of information on the impact of emissions, although not on the specific consequences of aviation emissions.

One approach for dealing with the impact of aviation on local air quality would be to include aviation in economywide pollution trading programs. Allowing aviation operators and entities from other industries to trade pollution permits could significantly reduce the total cost of meeting local emissions goals (FESG, 2001). Costs would be reduced because not all polluters or industries have the same technological and economic opportunities to reduce emissions; where substantial differences in cost exist, the lower-cost alternatives should be selected. Pollution trading programs would allow operators and, ultimately, consumers to face the full cost of compliance. It would also provide a framework for operators to benefit from using equipment with lower-than-required levels of emissions, by allowing them to sell their permits to entities with higher levels of emissions.

The shortfall in capacity at many airports also directly affects the amount of emissions produced. While FAA flow control programs do a good job of holding aircraft at gates when air traffic delays are building up, in many cases aircraft auxiliary power units continue to operate.[2] Also, when aircraft are released from a gate, they are often put into a long line for takeoff. Likewise, arriving aircraft can be sent to holding pens for long periods (with engines running) until gates are released. Automobile traffic can also build up during peak periods. Better matching of demand and capacity at airports would improve the local emissions picture.

Economic Costs of Emissions at Altitude

The economic consequences of climate change are potentially catastrophic in the long term. However, the contribution that aviation may be making to global warming and climate change is still uncertain. Because these are essentially global issues, they are best addressed through global institutions (i.e., ICAO), as discussed in Chapter 3.

SUMMARY

Currently, there are essentially no financial incentives for industry to develop and deploy environmental technologies that go beyond regulatory requirements. In fact, spending resources to go beyond regulatory requirements can put airlines at a competitive disadvantage. As a result, NASA research may generate new technology that the private sector has little or no incentive to adopt. Even so, mitigating the environmental impact of a growing air transportation system will require enlightened application of technology—and environmental policies should be framed to encourage industry to develop advanced environmental technologies and use them in operational products as they become available.

Finding 4-1. Environmental Impact. The environmental impact of any industry, including aviation, would be reduced if equipment manufacturers, service providers, and consumers directly faced the full costs of their activities, including environmental costs. For air transportation, this would require industry, consumers, and others who benefit from a robust air transportation system to face the full costs of operations.

Recommendation 4-1. Considering All Costs and Benefits. To support the formulation of environmental goals and air transportation policies, government and industry should invest in comprehensive interdisciplinary studies that quantify the marginal costs of environmental protection policies, the full economic benefits of providing transportation services while reducing the costs (in terms of noise, emissions, and congestion), and the potential of financial incentives to encourage the development and use of equipment that goes beyond regulatory standards.

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[2] Auxiliary power units are small jet turbines that provide aircraft with electrical power when the main engines are shut down and ground power is not connected.

5

A Call for Vigorous Federal Leadership

Every day, thousands of commercial aircraft take to the skies in the United States and across the globe, carrying people and materials on missions critical to the advancement of modern society. The success of aviation, however, has created a daunting paradox: demand for the rapid transportation it affords is so great that regional air traffic control systems and many airports are overloaded, causing chronic delays. Furthermore, because of the noise and emissions associated with contemporary aircraft operations, commercial aircraft are increasingly unwelcome in many of the cities they serve, especially in neighborhoods close to airports and the flight paths of arriving and departing aircraft. Thus, in the absence of major technological advance, the measures necessary to satisfy the demand for air transportation services often encounter fierce objections.

Federal, state, and local governments have established complex regulatory systems to limit the impact of aviation on the environment, and opponents of airport growth use these procedures to delay or stop the construction of new airports and the expansion of existing airports. Most often, the opposition to airport construction is based on perceptions about noise, but it may also be motivated by questions and concerns about the consequences of chemical emissions from aircraft engines for local air quality or global climate change.

Still, progress has been considerable. In 1975, some 70 million people near U.S. airports were exposed to an average community noise level of 55 dB DNL or more. (This is the noise level that is generally agreed to be a threshold above which substantial annoyance results from airport noise.) By 2000, action by airports, industry, and local, state, and federal governments had reduced the noise-affected population to about 5 million people. This was achieved through a combination of research and technology that led to quieter jet engines, regulations that required new and existing commercial aircraft to meet more stringent noise standards, improved operational systems and procedures, and heavy government investments in palliatives such as subsidizing purchases of additional land around airports, soundproofing buildings near airports, and rezoning property near airports to uses compatible with a relatively noisy environment. Even so, aviation remains caught between demands to provide more services and to decrease environmental impacts. Despite the continuation of expensive noise mitigation efforts, the total number of people exposed to high levels of aviation noise in the United States is not expected to decrease further for the next 20 years.

CONTEMPORARY FUNDING PATTERNS

The federal government has an established history of supporting research and technological solutions aimed at mitigating the adverse effects of aviation and thereby increasing the benefits of air transport to the nation. This report has surveyed the federal program of research related to the environmental compatibility of commercial aviation. NASA's current goals for reducing noise and emissions, as summarized in Table 1-4, are appropriate, although the timetable for achieving these goals is rather ambitious. In fact, achieving these goals is becoming increasingly difficult because of technological challenges, economic disincentives for industry to reduce noise and emissions below regulatory standards if doing so reduces competitiveness, and political factors that influence the allocation of available resources. The current timetable for achieving the goals is also unrealistic given the current level of funding and the time required for new technology to be incorporated in commercial products. Indeed, during the past 10 years, the federal government spent an average of about $450 million annually to reduce the impact of commercial aviation noise and emissions. However, less than one-third of this was devoted to the only approach for reducing environmental impact in the long term—research and technology that will lead to quieter, cleaner aircraft. Furthermore, each year for the past several years, a smaller fraction of total resources has been spent on research and tech-

TABLE 5-1 Comparison of Federal Expenditures for Noise Abatement (by the FAA) with Expenditures for Noise and Emissions Research and Technology (by the FAA and NASA)

Agency	Purpose of Expenditures	2001 Budget	Source of Funds
FAA Office of Airports	Noise abatement at individual airports	$500 million	Taxes and fees on airline tickets and air cargo shipments
NASA Office of Aerospace Technology	Technology development to reduce noise and emissions at the source	$55 million	Annual appropriation from general tax revenues
FAA Office of Environment and Energy	Research to better understand the impacts of noise and emissions and to develop new standards	$3 million	Annual appropriation from general tax revenues

nology; in 2001, more than 90 percent of available funds was spent on noise abatement (see Table 5-1 and Figure 5-1).

The current allocation of funding, which heavily favors airport noise abatement projects, is a consequence of the way funds are raised and appropriated. Most of these funds are raised from taxes on airline tickets for the purpose of subsidizing airport improvements, including noise abatement projects, and they are administered by the FAA through the Airport and Airway Trust Fund. Primary responsibilities for developing advanced aircraft technologies for source noise reduction, however, are assigned to NASA, which has no independent source of funding to support aeronautics research. Indeed, within NASA's constrained budget, aeronautics research has fared poorly in competing against higher-

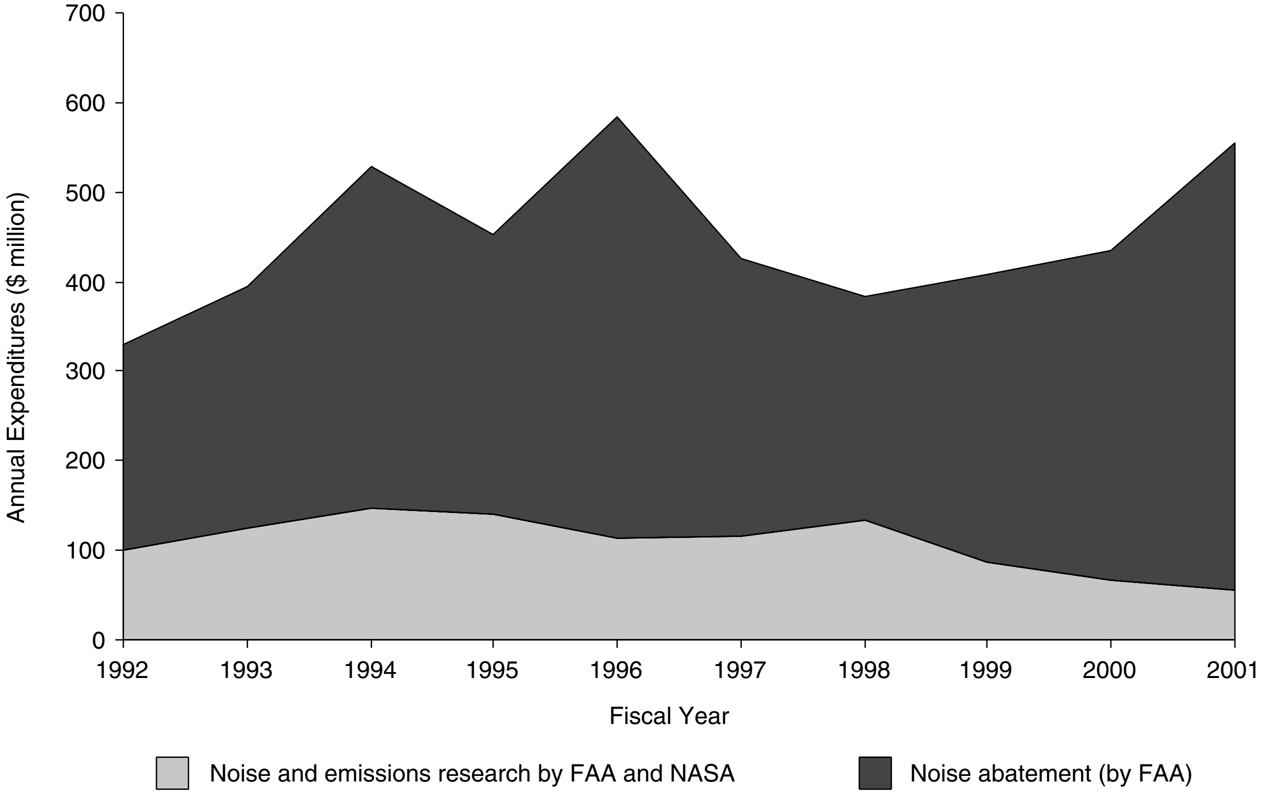

FIGURE 5-1 Comparison of federal expenditures for noise abatement (by the FAA) with expenditures for noise and emissions research and technology (by the FAA and NASA) (constant year 2000 dollars).

priority space programs. In constant year dollars, NASA funding for aeronautics research and technology was cut by about one-third between 1998 and 2000, reducing the breadth of ongoing research and prompting NASA to establish research programs with reduced goals, particularly with regard to TRL (technology readiness level). This significantly reduces the likelihood that the results of NASA research will find their way into the marketplace in a timely manner, if at all. The ultimate consequence is that federal expenditures are inconsistent with the long-term goal of supporting an aviation enterprise compatible with national goals for environmental stewardship.

The need to place more emphasis on noise research was noted in the fiscal year 2002 appropriations for the Department of Transportation, which directed that $20 million from the Airport and Airway Trust Fund be used to accelerate the introduction of noise-reducing aircraft technologies. These funds were provided to the Federal Aviation Administration, with the expectation that it would "work directly with" NASA to "advance aircraft engine noise research." Congress took this action because community opposition to aircraft noise is preventing the necessary expansion of some airports and because "aircraft noise results in millions of federal dollars being spent each year on mitigation measures, diverting funds which could be applied to capacity enhancement or safety projects" (Congress, 2001). The committee endorses this action as a first step in reducing the imbalance in the allocation of aircraft noise funding.

Looking to the future, it will be important for NASA periodically to reassess its environmental goals as atmospheric research reduces the uncertainties surrounding the impacts of various emissions and as regulatory and public health priorities change. In particular, it may be appropriate for NASA to adopt goals related to contrails and cirrus clouds. NASA research programs and FAA certification standards should also be developed with the understanding that emissions are an aircraft problem, not just an engine problem. In addition to advanced engine technology, changes in other areas—improved aerodynamics, lower structural weight, and improved aircraft operations—can also reduce emissions. Program plans should consider all options to ensure that expenditures are most likely to achieve established goals.

In addition to the FAA and NASA, other federal agencies (most notably the DoD) also support aviation noise and emissions research. DoD expects to spend an average of about $8 million per year (in constant year 2000 dollars) on aviation noise and emissions research between 2001 and 2008 (DoD, 2001). This level of funding may lead to worthwhile improvements in the noise and emissions performance of future military aircraft, but it is far less than the expenditures by NASA and the FAA and is insufficient to improve the situation significantly with regard to commercial aviation.

Finding 5-1. Status of Environmental Research. Research seeking to mitigate the environmental impacts of aviation is important to national and global well-being, but present efforts are operating with ambitious goals, unrealistic timetables for meeting them, and few and diminishing resources.

KEY ELEMENTS OF A RESEARCH STRATEGY

The value of research in reducing the impacts of aviation is evident, as shown by the quieter engines now available and the striking decrease in fuel consumed per revenue-passenger-kilometer. The energy required for powered flight has been reduced as engines and fuselages become more thermodynamically and aerodynamically efficient. But further improvements are becoming more difficult to achieve. Fuel consumed per passenger-kilometer was reduced by 57 percent between 1960 and 1998, but only 1/20th of the total improvement was achieved between 1990 and 1998. Meanwhile, demand is increasing more rapidly than noise or fuel per passenger-kilometer are being reduced. Even so the ultimate goals for noise and emissions remain uncertain, for several reasons:

- The impact of aviation on the environment is uncertain because the long-term effects of aircraft emissions locally, regionally, and globally are not well understood, especially with regard to high cloudiness and atmospheric chemistry.
- Aircraft emissions are only a small contributor to global atmospheric effects; therefore, goals for aircraft emissions would be most effective if established in the context of an overall scheme for controlling emissions, rather than focusing only on aircraft.
- In the very long term, solutions may involve changes in aircraft design as revolutionary as the change from pistons and propellers to turbojets or to a propulsion system using a new type of fuel.
- The level of noise that will ultimately prove acceptable to the general public, especially to people living near airports, is unknown. The current strategy has been to focus resources on areas where people are exposed to the worst noise, but a clear end point has not been established.

Regardless of these uncertainties, long-term growth in the demand for air transportation implies that the effects of aviation are certain to increase unless vigorous action is taken to achieve established goals in as timely a fashion as possible.

FOCUSING ON A NATIONAL STRATEGY AND A FEDERAL PLAN FOR ACTION

Nowhere in the world is there an air transportation system that provides services to as many people, at such a low price, with as much safety, and with as little environmental impact, as in the United States. Air transportation in the United States, however, is suffering from its success. Strong action is essential to avert a major collision between the growth of aviation and increasing concerns about the quality of the environment. Such a collision could damage aviation's role as a strong and efficient component of the U.S. economy and the national transportation infrastructure even more than the security concerns associated with attacks of September 11, 2001 (which amply illustrated the national economic consequences of a dysfunctional air transportation system). A national strategy and a federal plan for action are much needed. Two significant issues must be faced in developing such a national strategy: technology lead times and economic incentives.

Regarding technology lead times—with service lives of 25 to 40 years for individual models of commercial aircraft, it can take decades for a major technological improvement to show up in a majority of the commercial fleet. NASA, the FAA, and industry could reduce lead times by collaborating in the development of mature, proven technology that the FAA is willing to certify, airlines are willing to purchase, and manufacturers are willing to develop. All must work together to develop ideas, study their feasibility, develop prototypes, demonstrate readiness in flight tests, and in some cases provide economic incentives for rapid introduction into the fleet. Proven elements for improving the efficiency and effectiveness of technology collaborations by industry and government include the following:

- program goals clearly defined
- strong leader in government agency assigned
- system-level studies used to identify technical areas with highest payoff
- program promoted by stakeholders and high visibility established with senior agency executives and Congress
- commitment to full-length program and continuity of funding (7 to 8 years required to move from initial concept to TRL 6)
- contract vehicles established and technology transfer and protection policies defined early
- program metrics, roadmaps, and research plans defined early
- program established and implemented by organizations working as a national team
- research agency involved/partnered with operational agencies, industry, and universities early (e.g., by establishing technical work groups)
- steering committee composed of stakeholders established early

Regarding the second issue—economic incentives—government and the public must recognize the need for economic incentives for manufacturers and airlines to embrace technologies that minimize environmental impacts. Although passengers are unlikely to pay more to ride on an airplane with lower takeoff or approach noise, they may be willing to pay more to fly in a newer airplane that offers other advantages in addition to reduced environmental impacts. Over time, customers might even develop a preference for an airline that made environmental stewardship a goal almost as important as safety and service to customers.

More certain, however, is the ability of the government to establish economic incentives for using advanced environmental technologies. For example, a revenue-neutral change could be made to tax and fee structures so that quieter, cleaner aircraft pay lower taxes or fees than aircraft that generate more noise or higher levels of emissions. Alternatively, to support national environmental goals, the federal government could provide direct financial incentives to airlines that operate quieter aircraft with lower emissions just as the federal government now contracts with commercial airlines to participate in the civil reserve air fleet program to support national defense goals. During 1999, the federal budget for the civil reserve air fleet was more than $600 million.

The government is also responsible for ensuring that regulations and procedures that govern aircraft certification and operations facilitate the use of new technologies and changes in aircraft flight procedures whenever changes can reduce environmental impacts without sacrificing safety. Furthermore, as demonstrated by the phaseout of noisy but still flightworthy Stage 2 aircraft during the 1990s, the impact of aviation noise can be significantly reduced even when it imposes significant costs on the airlines, as long as it is supported by (1) a wide-ranging (in this case, global) consensus on the need for action and (2) technological solutions that government and industry have matured into new products certificated for commercial use.

Recommendation 5-1. Taking Advantage of Experience. The following lessons, learned since the advent of jet-powered aircraft, should be used to formulate and evaluate strategies for reducing the environmental effects of aviation:

- Success is not easy—it requires government support and federal leadership in research and development of new technology. Establishing a strong partnership involving federal, state, industry, and university programs is essential to progress.
- Changes in the impact of aviation on the environment occur on the scale of decades as fleets evolve; technological success in reducing adverse impacts occurs on the same or longer scales.
- The formulation of technological strategies to reduce the environmental impacts of aviation is hampered by significant uncertainties about (1) the long-term effects of aviation on the atmosphere, (2) economic factors associated with aircraft noise and emissions, and (3) the level of noise and emissions that ultimately will prove to be acceptable to airport communities and the general public, nationally and internationally.

Recommendation 5-2. Additional Research. To reduce conflicts between the growth of aviation and environmental stewardship, NASA, the FAA, and the EPA should augment existing research by developing specific programs aimed at the following topics:

- determining which substances identified by the EPA as hazardous air pollutants are contained in aircraft emissions and need to be further reduced
- understanding and predicting atmospheric response to aircraft emissions as a function of time on local, regional, and global scales
- exploring the suitability of alternate sources of energy for application to aviation, taking full account of safety and operational constraints

Recommendation 5-3. The Federal Responsibility. The U.S. government should carry out its responsibilities for mitigating the environmental effects of aircraft noise and emissions with a balanced approach that includes interagency cooperation and investing in research and technology development in close collaboration with the private sector and university researchers. Success requires commitment and leadership at the highest level as well as a national strategy and plan that does the following:

- coordinates agency research and technology goals, budgets, and expenditures with national environmental goals and international standards endorsed by the federal government
- periodically reassesses environmental goals and related research programs to ensure that they reflect current understandings of the impact of specific aircraft emissions on the environment and human health
- takes advantage of the unique expertise of both government and industry personnel and reverses the current trend of lessening industry involvement in NASA-sponsored environmental research and technology development
- reallocates funds in accordance with long-term goals, shifting some resources from short-term mitigation in localized areas to the development of engine, airframe, and operational/air traffic control technologies that will lead to aircraft that are quieter, operate more efficiently, and produce fewer harmful emissions per revenue-passenger-kilometer
- supports international assessments of the effects of aircraft emissions and the costs and benefits of various alternatives for limiting emissions
- expedites deployment of new technologies by maturing them to a high technology readiness level (i.e., technology readiness level 6, as defined by NASA) and providing incentives for manufacturers to include them in commercial products and for users to purchase those products

The U.S. aviation industry has struggled with serious capacity issues, conflicting expectations regarding delays and environmental impacts, and long-standing federal policies on the expenditure of funds that limit support for the very research that is the key to long-term success. Because aviation is critically important to individuals, the economy, and the nation, vigorous federal leadership must ensure that enlightened research and technology development proceed as rapidly as is scientifically possible.

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Findings and Recommendations

Given below is a complete list of the committee's findings and recommendations, in the order in which they appear in the report.

Finding 1-1. Increasing Rate of Fuel Consumption. Fuel consumption is a key indicator for assessing trends in emissions. The aviation industry is growing and the use of aviation fuel is increasing at a rate comparable to that of other uses of fossil fuels.

Finding 1-2. Vigorous Action Required. Environmental concerns will increasingly limit the growth of air transportation in the 21st century unless vigorous action is taken to augment current research and technology related to the environmental impacts of aviation.

Finding 2-1. Growing Cost of Noise. The cost of aviation noise is significant and growing. Aviation noise reduces property values, contributes to delays in expanding airport facilities, and prompts operational restrictions on existing runways that increase congestion, leading to travel delays, high airline capital and operating costs, and high ticket prices.

Finding 2-2. Technology Accomplishments and Goals. Over the past 30 years, the number of people in the United States affected by noise (i.e., the number of people who experience a day-night average sound level of 55 dB) has been reduced by a factor of 15, and the number of people affected by noise per revenue-passenger-kilometer has been reduced by a factor of 100. New technology has contributed significantly to these improvements.

Recommendation 2-1. Balanced Allocation of Funds. Federal expenditures to reduce noise should be reallocated to shift some funds from local abatement, which provides near-term relief for affected communities, to research and technology that will ultimately reduce the total noise produced by aviation. Currently, much more funding is devoted to local abatement than to research and technology. Also, to avoid raising unrealistic expectations, the federal government should realign research goals with funding allocations either by relaxing the goals or, preferably, by reallocating some noise abatement funds to research and technology.

Finding 2-3. Achieving Noise Reduction Goals. Additional technological advances now possible could move most objectionable noise within airport boundaries. However, the goal is unlikely to be achieved by NASA's target date of 2022, and achieving the goal may not fully alleviate the constraints that noise places on the aviation industry because of potential changes in the public's perception of the importance of a low-noise environment to quality of life.

Finding 2-4. Major Impediments. The most significant impediments to reducing the impact of aviation noise (or emissions) include long-term growth in the demand for aviation services, long lead times for technology development and adoption, long lifetimes of aircraft in the fleet, high development and capital costs in aerospace, high residual value of the existing fleets, and low levels of research and development funding.

Recommendation 2-2. Technology Maturity and Scope. NASA and other agencies should sustain the most attractive noise reduction research to a technology readiness level high enough (i.e., technology readiness level 6, as defined by NASA) to reduce the technical risk and make it worthwhile for industry to complete development and deploy new technologies in commercial products, even if this occurs at the expense of stopping other research at lower technology readiness levels. NASA and the FAA, in collaboration with other stakeholders (e.g., manufacturers, airlines, airport authorities, local governments, and nongovernmental organizations), should also support research to accomplish the following:

- Establish more clearly the connection between noise and capacity constraints.
- Develop clear metrics for assessing the effectiveness of NASA and FAA noise modeling efforts.
- Implement a strategic plan for improving noise models based upon the metrics.
- Harmonize U.S. noise-reduction research with similar European research.

Recommendation 2-3. Interagency Coordination. Interagency coordination on aircraft noise research should be enhanced by ensuring that the members of the Federal Interagency Committee for Aircraft Noise have budget authority within their own organizations to implement a coordinated strategy for reducing aviation noise.

Finding 3-1. Gap Between Technology and Demand. Continuation of ongoing technology research will reduce fuel consumption per revenue-passenger-kilometer by about 1 percent per year over the next 15 to 20 years. During the same time, the demand for air transportation services is expected to increase by 3 to 5 percent per year. An aggressive, broad-based technology program that encompasses propulsion systems, the airframe, and operational systems and procedures could significantly close this gap. Existing allocations of research funding and funding trends within NASA and the FAA do not support such a program.

Finding 3-2. Gap Between NASA Goals and Programs. NASA funding to achieve its goals for reducing CO_2 and NO_x emissions is insufficient to reach the specified milestones on time. Little or no funding is available for research related to other emissions, such as hydrocarbons, particulates, and aerosols, which may also have significant effects on the atmosphere locally, regionally, or globally.

Recommendation 3-1. Research on Global, Regional, and Local Emissions. NASA should continue to take the lead in supporting federal research to investigate the relationships among aircraft emissions (CO_2, water vapor, NO_x, SO_x, aerosols, particulates, unburned hydrocarbons, and other hazardous air pollutants) in the stratosphere, troposphere, and near the ground, and the resulting changes in cirrus clouds, ozone, climate, and air quality (globally, regionally, and locally, as appropriate). Other agencies interested in aircraft or the environment should also support basic research related to these programmatic goals.

Recommendation 3-2. Eliminating Uncertainties. NASA should support additional research on the environmental effects of aviation to ensure that technology goals are appropriate and to validate that regulatory standards will effectively limit potential environmental and public health effects of aircraft emissions, while eliminating uncertainties that could lead to unnecessarily strict regulations.

Finding 4-1. Environmental Impact. The environmental impact of any industry, including aviation, would be reduced if equipment manufacturers, service providers, and consumers directly faced the full costs of their activities, including environmental costs. For air transportation, this would require industry, consumers, and others who benefit from a robust air transportation system to face the full costs of operations.

Recommendation 4-1. Considering All Costs and Benefits. To support the formulation of environmental goals and air transportation policies, government and industry should invest in comprehensive interdisciplinary studies that quantify the marginal costs of environmental protection policies, the full economic benefits of providing transportation services while reducing the costs (in terms of noise, emissions, and congestion), and the potential of financial incentives to encourage the development and use of equipment that goes beyond regulatory standards.

Finding 5-1. Status of Environmental Research. Research seeking to mitigate the environmental impacts of aviation is important to national and global well-being, but present efforts are operating with ambitious goals, unrealistic timetables for meeting them, and few and diminishing resources.

Recommendation 5-1. Taking Advantage of Experience. The following lessons, learned since the advent of jet-powered aircraft, should be used to formulate and evaluate strategies for reducing the environmental effects of aviation:

- Success is not easy—it requires government support and federal leadership in research and development of new technology. Establishing a strong partnership involving federal, state, industry, and university programs is essential to progress.
- Changes in the impact of aviation on the environment occur on the scale of decades as fleets evolve; technological success in reducing adverse impacts occurs on the same or longer scales.
- The formulation of technological strategies to reduce the environmental impacts of aviation is hampered by significant uncertainties about (1) the long-term effects of aviation on the atmosphere, (2) economic factors associated with aircraft noise and emissions, and (3)

the level of noise and emissions that ultimately will prove to be acceptable to airport communities and the general public, nationally and internationally.

Recommendation 5-2. Additional Research. To reduce conflicts between the growth of aviation and environmental stewardship, NASA, the FAA, and the EPA should augment existing research by developing specific programs aimed at the following topics:

- determining which substances identified by the EPA as hazardous air pollutants are contained in aircraft emissions and need to be further reduced
- understanding and predicting atmospheric response to aircraft emissions as a function of time on local, regional, and global scales
- exploring the suitability of alternate sources of energy for application to aviation, taking full account of safety and operational constraints

Recommendation 5-3. The Federal Responsibility. The U.S. government should carry out its responsibilities for mitigating the environmental effects of aircraft noise and emissions with a balanced approach that includes interagency cooperation and investing in research and technology development in close collaboration with the private sector and university researchers. Success requires commitment and leadership at the highest level as well as a national strategy and plan that does the following:

- coordinates agency research and technology goals, budgets, and expenditures with national environmental goals and international standards endorsed by the federal government
- periodically reassesses environmental goals and related research programs to ensure that they reflect current understandings of the impact of specific aircraft emissions on the environment and human health
- takes advantage of the unique expertise of both government and industry personnel and reverses the current trend of lessening industry involvement in NASA-sponsored environmental research and technology development
- reallocates funds in accordance with long-term goals, shifting some resources from short-term mitigation in localized areas to the development of engine, airframe, and operational/air traffic control technologies that will lead to aircraft that are quieter, operate more efficiently, and produce fewer harmful emissions per revenue-passenger-kilometer
- supports international assessments of the effects of aircraft emissions and the costs and benefits of various alternatives for limiting emissions
- expedites deployment of new technologies by maturing them to a high technology readiness level (i.e., technology readiness level 6, as defined by NASA) and providing incentives for manufacturers to include them in commercial products and for users to purchase those products

Appendices

A

Biographies of Committee Members

John A. Dutton (chair) is professor of meteorology and dean of the College of Earth and Mineral Sciences at Pennsylvania State University. Dr. Dutton previously served as chair of the Board on Atmospheric Sciences and Climate of the National Research Council (NRC), was a member of the NRC National Aviation Weather Services Committee, and has served as a member on numerous other NRC committees. Dr. Dutton served for many years as chairman of the board of directors of the University Corporation for Atmospheric Research Foundation. He is a fellow of the American Meteorological Society and the American Association for the Advancement of Science. Dr. Dutton holds three degrees in meteorology from the University of Wisconsin and served as an officer in the Air Weather Service of the U.S. Air Force. His expertise includes dynamic meteorology, spectral modeling, climate theory, and global change. He has authored two textbooks in atmospheric science and a variety of articles on the dynamics of atmospheric motion. Dr. Dutton is an active general aviation pilot with multiengine and instrument ratings.

Donald Bahr, a member of the National Academy of Engineering (NAE), was manager of the Combustion Technology Operation at GE Aircraft Engines for more that 20 years. He joined GE Aircraft Engines in 1956 as a combustion research engineer. As manager, he was responsible for the design, development, and certification of a variety of combustion systems used in both commercial and military aircraft turbine engines, as well as combustion systems used in industrial turbine engines. Mr. Bahr graduated from the University of Illinois with a B.S. degree in chemical engineering and from the Illinois Institute of Technology with M.S. degrees in chemical engineering and gas technology. He is a fellow of the American Society of Mechanical Engineers (ASME) and the American Institute of Aeronautics and Astronautics (AIAA). He is a member of the General Electric Propulsion Hall of Fame.

Frank Berardino is president of GRA, Incorporated, with 25 years of professional consulting experience. He has directed several airline acquisition or divestiture studies for major airlines in the United States and overseas. Mr. Berardino has also recently directed studies for both public and private clients on issues related to airline access to airports in the United States and overseas. He has served as project manager of various environmental projects for the Federal Aviation Administration (FAA) and has testified as an expert witness in several legal cases and regulatory proceedings. Mr. Berardino has a B.A. in economics from Kenyon College and an M.A. in economics from the University of Pittsburgh. He specializes in applied microeconomics of regulated industries, including aviation, railroading, and other modes of transportation.

Benjamin A. Cosgrove, NAE, is a retired senior vice president of the Boeing Commercial Airplane Group. His career as a structural engineer began at Boeing in 1949 on the B-47 and B-52 bombers. He was involved in the design and analysis of every Boeing commercial airplane from the 707 through the 777. Mr. Cosgrove was the chief design engineer of the 767, became vice president of engineering and flight testing in 1985, and was promoted to senior vice president in 1989. He is a member of the National Academy of Engineering and received an honorary doctorate of engineering from the University of Notre Dame. Mr. Cosgrove is also a member of the NASA Advisory Council's Task Force on the Shuttle-Mir Rendezvous and Docking Missions and the Task Force on International Space Station Operational Readiness.

Randall Guensler is an associate professor in the School of Civil and Environmental Engineering at Georgia Institute of Technology. He has been chairman of the Transportation Research Board's Committee on Transportation and Air Quality since 1997. He has published an article on environmental impact assessment. Dr. Guensler has been a fellow for the Eno Foundation Transportation Leadership, Chevron Corporation Research, Institute of Transportation Studies, and the U.S. Environmental Protection Agency, as well as a scholar for the Air & Waste Management Association. He received a sustained superior accomplishment award from the California Air Resources Board. Dr. Guensler's research focuses on transportation and the environment. Research interests include relationships between land use, infrastructure, travel behavior, and vehicle emission rates; transportation and air quality planning and modeling—theory and practice; emission control strategy effectiveness and economic/equity impacts; and environmental impact assessment and environmental ethics.

S. Michael Hudson is retired vice chairman of Rolls-Royce North America Holdings Inc. Previously he was president of Rolls-Royce Allison, executive vice president of engineering for Allison Engine Company, and general director of engineering for Allison Gas Turbine Division under the ownership of General Motors Corporation. He has also served as president of both Rolls-Royce Defense North America and Rolls-Royce Helicopter Units. Mr. Hudson served as chief engineer for advanced technology, chief engineer for small production engines, chief of preliminary design, and chief project engineer in vehicular gas turbines during his tenure at Allison. Before joining Allison he was employed by Pratt & Whitney Aircraft, working in engine design, installation, and performance, and industrial and marine application engineering.

Nicholas P. Krull held several positions with the FAA. Before retiring in 1995, he served as chief scientific and technical officer, director of the Technology Division, and manager of the Engines and Fuels Programs. Prior to joining the FAA, Mr. Krull was with American Airlines as director of space programs and director of new aircraft configuration management. Mr. Krull has also served as technical advisor to the U.S. representative to the International Civil Aviation Organization (ICAO) and on several committees. He has served on the NRC's Panel on Atmospheric Effects of Aviation. His fields of expertise include atmospheric emissions, noise pollution, and environmental standards and regulations.

Rich Niedzwiecki retired in 1999 from NASA, where he had served as a senior engineer in aeronautics for combustion and emissions research and also as the chief of the Combustion Technology Branch, Propulsion Division, at the Lewis Research Center in Ohio. After retirement, Mr. Niedzwiecki has been involved in developing a report on aviation and the global environment through the Intergovernmental Panel on Climate Change, an organization established by the World Meteorological Organization and the United Nations Environment Programme. He has also assisted in the preparation of a NASA report on the High Speed Research Program. Mr. Niedzwiecki is currently finalizing plans to assist the U.S. Air Force in determining the environmental impacts of military aircraft.

Akkihebal R. Ravishankara, a member of the National Academy of Sciences, is involved in the application of laboratory chemical kinetics to global environmental issues. His work includes many fundamental contributions to the understanding of the gas-phase and surface chemistry that controls atmospheric ozone, as well as the key chemistry of climate-relevant gases, and gases contributing to global atmospheric pollution. Dr. Ravishankara has measured many critical chemical reactions and processes with innovative methods, providing much of the current quantitative understanding of ozone depletion, chemical forcing of Earth's climate system, and photochemical smog production. Currently, he acts as chief of the Atmospheric Chemical Kinetics Group at the National Oceanic and Atmospheric Administration. He is an adjoint professor of chemistry at the University of Colorado, Boulder. He serves on many panels and is currently an editor for *Geophysical Research Letters*.

Bradford Sturtevant (deceased) was the H.W. Liepman Professor of Aeronautics at the Graduate Aeronautical Laboratories, California Institute of Technology. He served as executive officer and option representative for aeronautics. Previously, Dr. Sturtevant held several visiting lecturer posts as the Gordon MacKay Lecturer on Fluid Mechanics at Harvard University; at the Institute for Aerospace Studies, Technical University, Aachen, Germany; at the Indian Institute of Technology, Bangalore, India; and, as visiting professor of geology, Bristol, England. He was a fellow of the American Physical Society and active in the AIAA, the American Geophysical Union, the Acoustical Society of America, the Society of Automotive Engineers, and the American Association for the Advancement of Science. His teaching and research interests included gas dynamics and two-phase flow, with emphasis on shockwave dynamics, transient flows, and explosion phenomena.

Ray Valeika has been senior vice president of technical operations for Delta Air Lines since October 1996. Previously he served as vice president of technical operations for Delta and as senior vice president of technical operations for Continental Airlines. Mr. Valeika has chaired numerous committees and provided leadership for many of the industry's technological innovations. He chaired the Air Transport Association's original Aging Aircraft Task Force, which developed supplemental structural inspection programs.

Ian A. Waitz is a professor of aeronautics and astronautics at the Massachusetts Institute of Technology (MIT), where he is associate director of the MIT Gas Turbine Laboratory and director of the Aero-Environmental Research Laboratory. His principal fields of interest include propulsion, fluid mechanics, thermodynamics, reacting flows, aeroacoustics, and, in particular, aspects of these areas that relate to environmental issues associated with aircraft design and operation. Dr. Waitz has published extensively in these areas. He has served as an associate editor of the AIAA *Journal of Propulsion and Power* and is an associate fellow of the AIAA and a member of ASME and the American Society for Engineering Education. He currently teaches graduate and undergraduate courses in the fields of thermodynamics and energy conversion, propulsion, fluid mechanics, and the environmental effects of aircraft.

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

B

Acronyms and Abbreviations

AIP	Airport Improvement Program
ASEB	Aeronautics and Space Engineering Board
CO	carbon monoxide
CO_2	carbon dioxide
dB	decibel
DNL	day-night average sound level
DoD	Department of Defense
EPA	Environmental Protection Agency
EPN dB	effective perceived noise level in decibels
FAA	Federal Aviation Administration
FARs	Federal Aviation Regulations
HSCT	high speed civil transport
HSR	High Speed Research (program)
ICAO	International Civil Aviation Organization
IMC	instrument meteorological conditions
INM	Integrated Noise Model
IPCC	Intergovernmental Panel on Climate Change
MAGENTA	Model for Assessing the Global Exposure to the Noise of Transport Aircraft
MTOW	maximum takeoff weight
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NO_x	oxides of nitrogen
NRC	National Research Council
PFC	Passenger Facility Charge (program)
QAT	Quiet Aircraft Technology (program)
SO_x	oxides of sulfur
TRL	technology readiness level
UV	ultraviolet