Data and Analysis for Aviation R&D

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"I find it very *difficult to make a choice between an aggressive R&D program on aging aircraft, non-destructive testing, terrorism, runway incursions, [or] collision avoidance. I don 't know how one* says *that one is more important than the other We try to do them all. We try to do them all with what we have to work with."*[1]

Resources for aviation research and development (R&D) are limited. Deciding how to allocate these resources among competing areas of interest and obligation is made even more difficult by the lack of assurance that the R&D effort will yield a usable product. Furthermore, tension exists between committing resources to immediate problem solving and longer term problem identification efforts, whether for continuing challenges or emerging issues. There is growing emphasis on understanding the economic effects of technology implementation (through regulatory or infrastructure decisions), given a financially strapped aviation industry that in the best of times only produces razor-thin profit margins. But not all problems or potential solutions can be quantified easily in terms of financial impact, and standard cost-benefit analyses are of limited use in planning R&D.

Criteria for selecting federal research projects include scientific merit (i.e., does it complement or deepen existing knowledge), program or mission relevance, technology-base expansion, balance between large and small, and enhancement of human re-

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[1] Joseph Del Balzo, Executive Director for System Development, Federal Aviation Administration, testimony at hearings before the House Committee on Space, Science, and Technology, Subcommittee on Transportation, Aviation, and Materials, Mar. 6,1990.

sources and education.[2] For civil aviation, many of these criteria are less important than solving pressing operational problems, primarily through targeted R&D efforts. Selecting options for applied R&D resources suggests different criteria: size of problem, feasibility and net cost of solutions, and level of understanding of the problem. Where the last is low, gauging size is difficult, in turn affecting one's ability to develop potential solutions and estimate their benefits; more data and R&D are needed (e.g., on human performance, complex systems, or new materials).

Table 3-1 summarizes the performance objectives for R&D, along with technology options and their limitations, in four areas. This chapter outlines the historical benefits of aviation R&D and provides a framework for analyzing the potential payoff of R&D efforts across as well as within the Federal Aviation Administration (FAA) missions. It also discusses the usefulness of cost-benefit calculations for setting R&D priorities and delineates further data or analyses needs—information to support both continued problem-solving activities and improved problem prediction efforts.

HISTORICAL PAYOFFS OF AVIATION R&D

In examining the potential payoffs of R&D, the Office of Technology Assessment (OTA) first looked to how well-known problems have been addressed or resolved in the past. The key concerns of the aviation community in the 1970s included mid-air collisions, noise and fuel efficiency, and hijacking. By the early 1980s, new issues emerged—safety oversight, traffic improvements, and aircraft bombings—and noise abatement continued to be a concern.

I Safety

Major accident data for Part 121 carriers reveal that safety has improved dramatically over the lifetime of the industry (figure 3-1).[3] The reduced accident rates for Parts 121 and 135 operations, shown in figure 3-2, resulted from repeated introduction of safety technologies and procedures, many based on federal R&D conducted through the years. For fire safety in particular, the federal government spent nearly a decade devising appropriate test scenarios, evaluating safety improvements provided by fire retardant materials, developing test methodologies for materials selection, and initiating rulemaking.[4] In the public's eyes, however, more remains to be done with cabin safety, which requires further study of the basic mechanisms of fire development. Also, because cabin interior materials technology is state-of-the art and because additional fire sources exist (e.g., jet fuel, cargo and luggage, and carry-on items), FAA is looking toward other means of fire


NATIONAL TRANSPORTATION SAFETY BOARD

New technologies have helped to improve *aircraft tire safety and reduce tire-related fatalities, however postcrash, fuel-fed fires remain a threat*

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[2] See discussion of prioritization in science in U.S. Congress, Office of Technology Assessment, *Federally Funded Research: Decisions for a Decade, OTA-SET-490* (Washington, DC: U.S. Government Printing Office, May 1991).

[3] A major accident involves fatalities and or substantial aircraft damage. Parts 121 and 135 refer to the major commercial carriers and commuter airlines, respectively.

[4] See U.S. Congress, Office of Technology Assessment, "Aircraft Evacuation Testing: Research and Technology Issues," Background Paper, OTA-SET-BP- 121, September 1993.

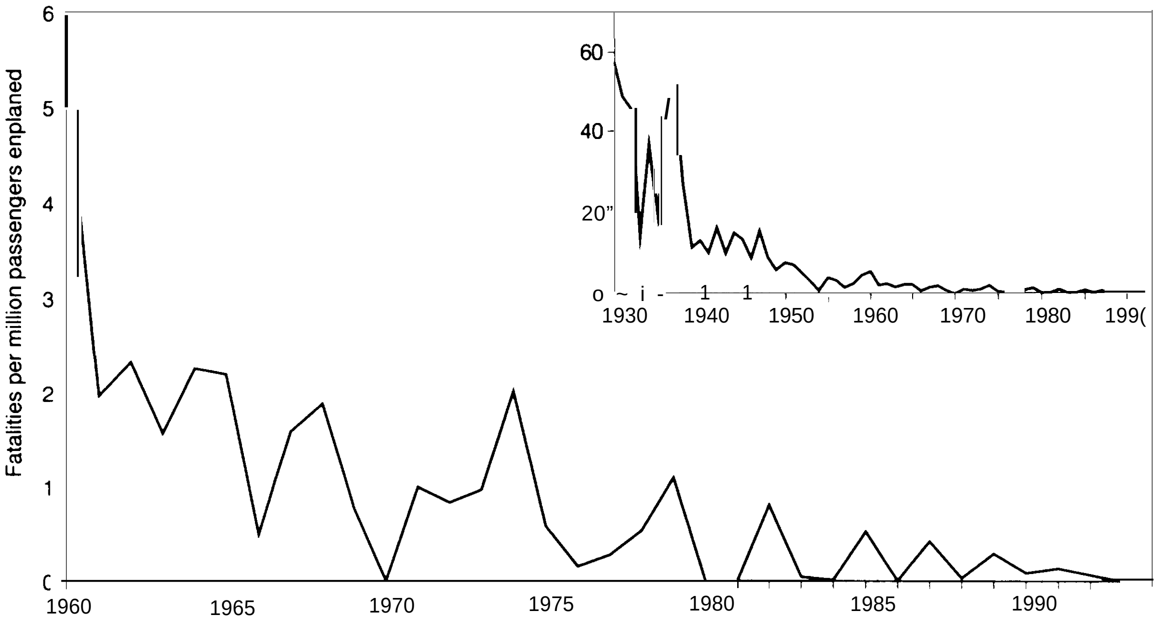
[redacted]

Issue	Potential improvements	Technology options	Limitations
Airspace and airport efficiency	Closer spacing between aircraft and increased aircraft arrival and departure rates at airports without increased risk of collision Augmented airport surface traffic management capabilities, especially in low-visibility conditions	Enhanced communications, navigation, and surveillance technologies and procedures, including the global navigation satellite system, advanced traffic management tools, wake vortex detection	Technologies are site-specific, and for many, complex procedures must be revised or adapted for their use While use of new ATC and weather technologies can reduce airline operating costs and infrastructure expenditures, this technology will meet but a small percentage of projected demand in coming decades Demand management options discounted by industry
	Oceanic separations equivalent to those in domestic airspace	Satellite-based communications, navigation, and surveillance systems, automatic dependent surveillance via datalink	Procedures subject to lengthy validation and international agreement process Initial benefits to airlines small until fleet-wide implementation is accomplished Ground-based monitoring equipment required before automatic dependent surveillance can begin
	Improved reliability and accuracy of weather forecasts	Advanced weather detection and analysis systems, cockpit display of aviation weather products (e g , icing at given altitudes or jet stream location)	Human/machine interface must be considered, and increased amount of information must not overwhelm pilot or controller
	Minimal runway downtime	Enhanced pavement construction and maintenance techniques	Pavement design and evaluation methods require improvement
	Reduced apron and gate occupancy times	High-speed tugs, advanced docking technologies, automated gate assignment techniques, integrated passenger, baggage, crew, and vehicle information systems	Divisions between airport and airline authority Onerous retrofit costs for communication systems, and terminal and airside access facilities
Safety	Enhanced pilot and controller awareness of aircraft situation in all conditions Reduced personnel fatigue and stress Improved crew communication and coordination improved reliability of engines, avionics, and other aircraft systems Reduced fire threat Enhanced structural airworthiness and crashworthiness	Enhanced training methods and facilities Advanced inspection tools and techniques New materials Predictive hazardous weather sensors and severe storm forecasting	Diminishing returns—fewer lives to be saved even with exhaustive effort Overall risk may be increased by adopting new technologies or procedures
Security	Minimized risk of explosives and other weapons being brought onboard aircraft Enhanced aircraft resilience to explosions Reduced threat to ATC and airports Optimized costs of screening technologies and airport security service costs	Passenger profiling, explosives detection systems, other weapons detectors, aircraft and ATC system hardening human factors analysis	No single technology exists for preventing all acts of terrorism or mayhem Threat cannot be quantified Screening methods are costly and time consuming, and access control and hardening techniques costly
Environment	Minimum community noise exposure maintained as operations increase Minimized engine emissions and increased fuel efficiency Reduced environmental impact of deicing and fire fighting compounds Improved cabin environment	Additional noise cancellation and community noise abatement methods, low-emissions combustors, reclamation of glycol-based fluids and replacement with non-glycol deicers, halon conservation and halon-system replacement	Except for improved fuel performance, any economic benefits accrue to society rather than to airlines Scientific understanding lacking in some areas, problem not quantified

KEY ATC = air traffic control

SOURCE Office of Technology Assessment, 1994

FIGURE 3-1: Passenger Fatality Rates for Scheduled U.S. Air Carriers



NOTE Security-related fatalities and suicides are not Included

SOURCE Office of Technology Assessment, 1994, based on Civil Aeronautics Board, Federal Aviation Administration, and National Transportation Safety Board data

suppression to extend survivable conditions within a cabin threatened by in-flight or postcrash fuel fires. (See cabin safety section in chapter 4.)

In some cases, a relatively low-technology solution is appropriate once the nature of a problem is known. During the period 1975 to 1985, windshear was a factor in accidents resulting in 50 percent of U.S. accident fatalities. After the phenomenon was widely recognized and better understood, FAA and industry were able to quickly put together a new training program for pilots to increase their awareness of the problem and provide them with better response capability. Although there have been close calls for commercial transports since then, no windshear-related passenger fatalities occurred in the United States after 1985, when the training aid was disseminated.[5]

Environment

The National Aeronautics and Space Administration (NASA) research during the 1960s and 1970s greatly aided fuel conservation efforts by developing highly efficient engines. In 1975, NASA's Aircraft Energy Efficiency (ACEE) program identified turboprops, along with laminar flow, active controls, and composite structures, as areas for

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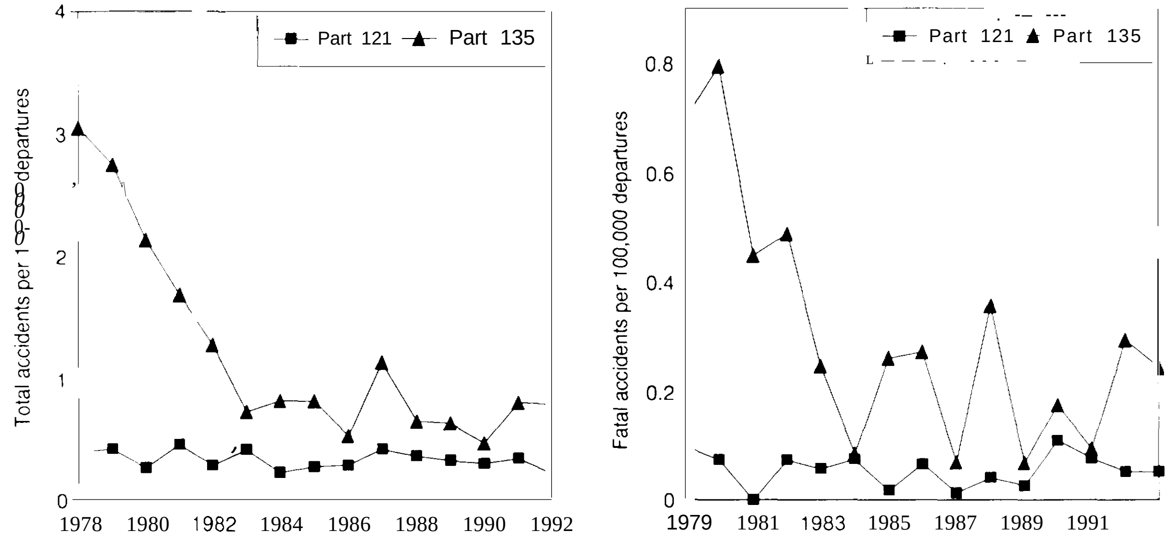
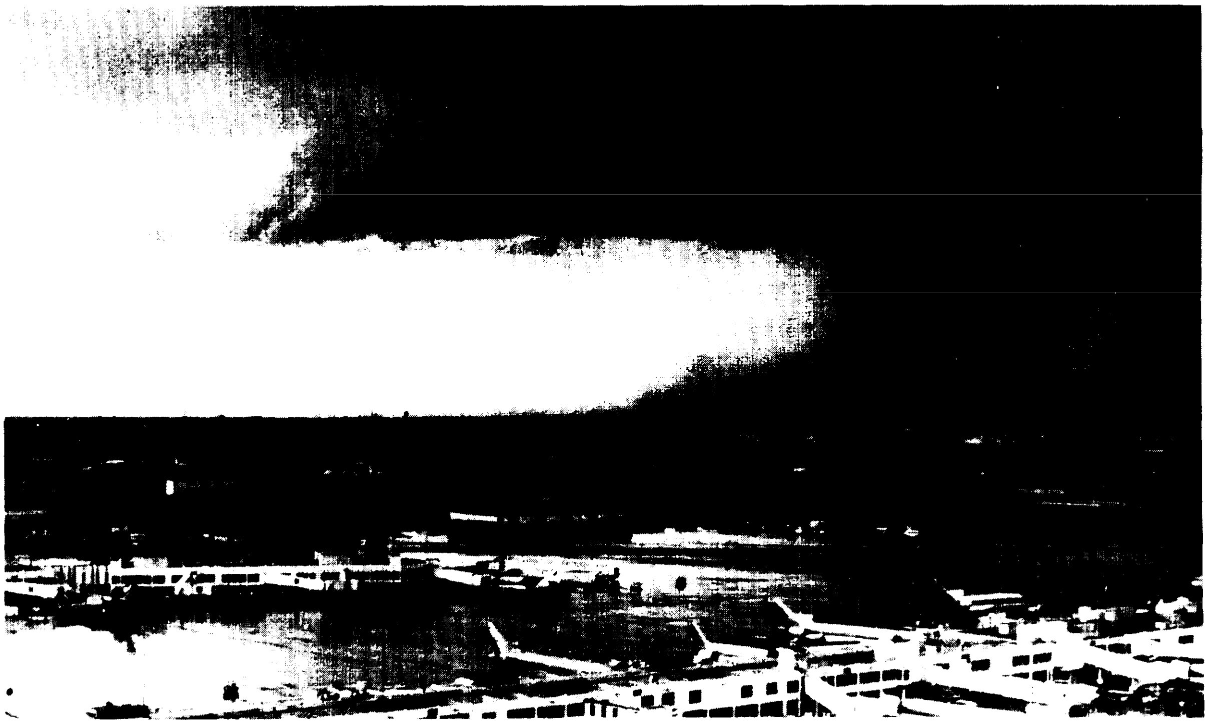
[5] As the understanding of windshear factors and phenomena has increased, new sensors allowing earlier warning of the hazard have become possible (see technology section inch. 4). Windshear may have been a causal factor in the July 1994 USAir crash in Charlotte, NC; determination of the probable cause of the accident will take many months.

FIGURE 3-2: Accident Rates for Scheduled Part 121 and Part 135 Carriers, 1978-92



NOTE Part 121 of the Federal Aviation Regulations is typically associated with the major airlines and Part 135 with commuter aircraft with fewer than 30 seats

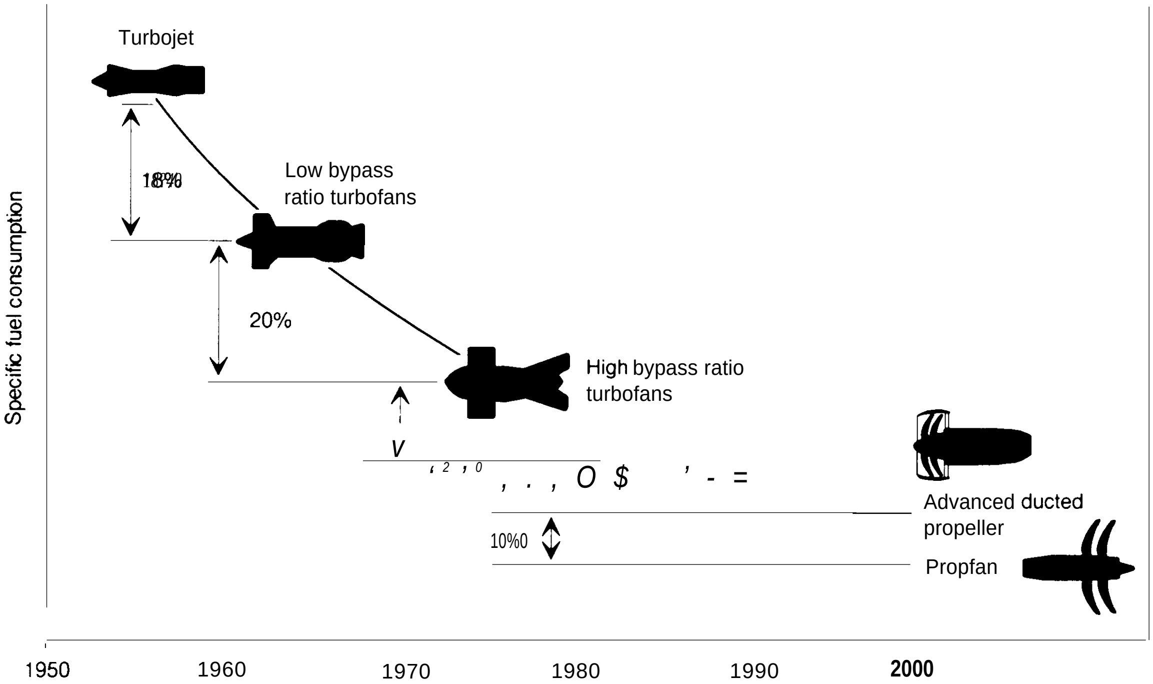
SOURCE Office of Technology Assessment based on 1989 and 1993 National Transportation Safety Board data



NATIONAL CENTER FOR ATMOSPHERIC RESEARCH/NATIONAL SCIENCE FOUNDATION

Visible windshear indicators observed near Denver Stapleton Airport

FIGURE 3-3: Fuel Efficiency Trend in Aircraft Engine Design



SOURCE Office of Technology Assessment, 1994, based on 1993 Pratt &Whitney information

major advances in fuel efficiency.[6] The ACEE program included the Engine Component Improvement (ECI) and Energy Efficient Engine (E^3) projects. ECI was designed to develop components to reduce fuel consumption for three engine designs in use at the time. E^3 consisted of long-term research for new engine development; demonstration engines achieved a fuel consumption reduction of 18 percent and an improvement indirect operating costs of 5 to 10 percent, exceeding the project's original goals.[7] The results are illustrated in figure 3-3.

NASA's clean, quiet engine programs also permitted engine manufacturers to reduce emissions of combustion products and noise in response to federal regulatory initiatives. In 1968, Congress authorized FAA to regulate aircraft noise emissions.[8] Under that statutory authority, FAA adopted Part 36 of the Federal Aviation Regulations (FAR) in 1969, prohibiting the further es-

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[6] John S. Langford III, The *NASA Experience* in *Aeronautical R&D: Three Case Studies With Analysis*, IDA Report R-319 (Alexandria, VA: Institute for Defense Analyses, March 1989), p. 112.

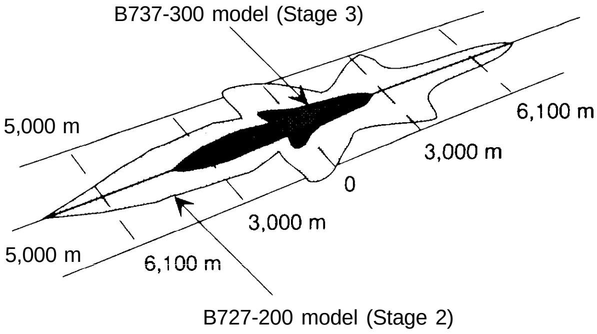
[7] George Eberstadt, "Government Support of the Large Commercial Aircraft Industries of Japan, Europe, and the United States," OTA contractor report, May 1991, pp. 75-76.

[8] Public Law 90-411, 82 Stat. 395 (1968).

calation of aircraft noise levels in subsonic civil turbojet and transport category airplanes and prescribing noise measurement, evaluation, and level requirements for new aircraft types.[9] In 1977, FAA amended Part 36 to provide for three stages of aircraft noise levels.[10]

Through the Aviation Noise and Capacity Act of 1990, Congress directed the elimination of Stage 2 operations by the end of the century.[11] In September 1991, FAA promulgated a final rule amending FAR Part 91 to require the phased transition to all Stage 3 commercial aircraft operations by December31, 1999. The Stage 3 technology provides improvements of as much as 25 decibels over first-generation Stage 1 aircraft models, or over 80-percent reduction in perceived loudness.[13] Figure 3-4 shows one result of a drop in noise output normalized to thrust (i.e., the relative footprints of Boeing 727 and 737 aircraft).

FIGURE 3-4: Relative Noise Footprints for B727 and B737 Aircraft



SOURCE Office of Technology Assessment, 1994 based on William Green et al *Modern Commercial Aircraft* (New York NY Portland House 1987)

The Environmental Protection Agency (EPA) data indicate the quantity of air pollutant emissions has remained fairly constant over more than two decades despite continued growth in operations (see figure 3-5). However, FAA estimates that hydrocarbon (HC) and carbon monoxide (CO) emissions have dropped 65 to 70 percent since 1984, when emission standards were introduced.[14] This reduction more than offsets increases in total fuel consumption. The disparity in estimates may stem from differences in the agencies' databases and changes in analytic methodologies (see section on Environmental Assessment).

EPA regulates only HC emissions: the International Civil Aviation Organization (ICAO) has standards for CO and oxides of nitrogen (NO_x) as well as HC.[15] In the past. emissions from highly efficient engines have easily met the international minimums. Beginning in 1996, however, new engine designs must meet the 20-percent reduced NO_x standard; by 2000, all newly manufactured engines must meet the more stringent standard.[16] In addition, some locations in the United States

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[9] Part 36 noise limitations, based on gross weight, are measured at three specific points: under the takeoff path, on the sideline from the extended centerline of the runway, and under the approach path. At each of these points, the effective perceived noise level takes into account loudness, discrete tones, and noise event duration. FAA developed the standards in concert with the Environmental Protection Agency.

[10] 42 *Federal Register* 12360 (Mar. 3, 1977). Stage I is the noisiest; Stage 3 is the quietest to date.

[11] 45 *Federal Register* 79302 (Nov. 28, 1980).

[12] 56 *Federal Register* 48627 (Sept. 25, 1991). Some exemptions are possible until 2004.

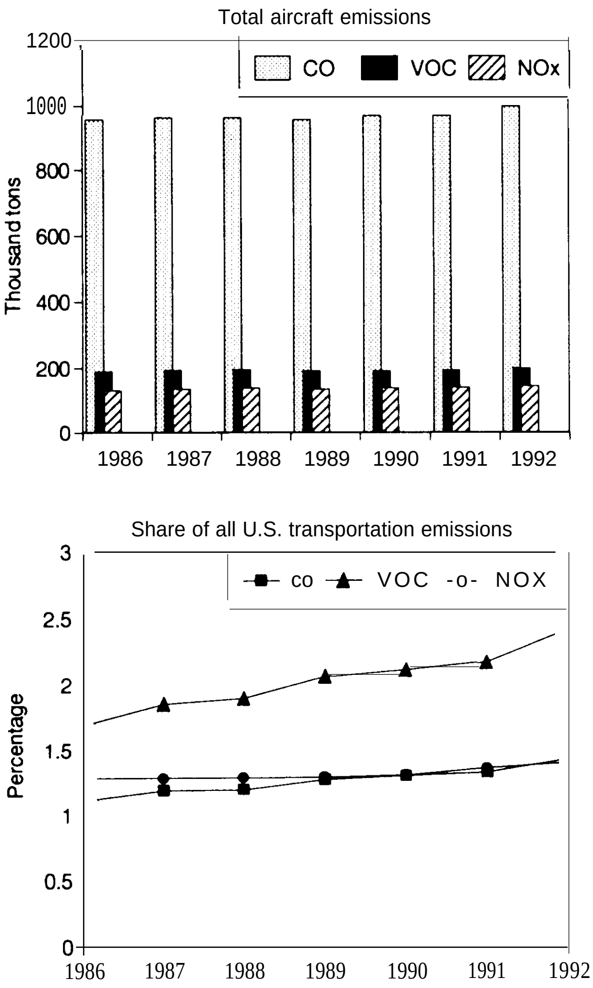
[13] U.S. Department of Transportation, Federal Aviation Administration, "Alternatives Available To Accelerate Commercial Aircraft Fleet Modernization," Report of the Federal Aviation Administration to the Senate and House Appropriations Committees Pursuant to House Report 99-256 on the Department of Transportation and Related Agencies Appropriation Bill for FY 1986, Apr. 11, 1986, p. 13.

[14] NO_x emissions have remained nearly constant. Nicholas Krull, FAA Office of Environment and Energy, personal communication, Apr. 28, 1994.

[15] Jim Bryson, EPA Office of Mobile Sources, personal communication, Apr. 7, 1994.

[16] Adopted in March 1993. Ibid.

FIGURE 3-5: U.S. Aircraft CO, VOC, and NO_x Emissions, 1988-92



NOTE In the mid-1980s, changes occurred in the methodology for estimating emissions.

KEY: CO= carbon monoxide, VOC = volatile organic compounds (e g , hydrocarbons); NO_x = oxides of nitrogen.

SOURCE Office of Technology Assessment, 1994, based on U S Environmental Protection Agency, *National Air Pollutant Emission Trends, 1990-1992* (Research Triangle Park, NC October 1993)

may require total airport "bubble" emissions to stabilize or even be reduced.[17] Much of this can be accomplished through modifications to ground-assist equipment, reduced taxi/idle time, or the use of high-speed towing equipment, but reduced aircraft engine emissions may also be necessary eventually.[18]

Security

As federal intervention (i.e., increased vigilance and the implementation of improved weapons detection technologies) reduced the hijacking threat, terrorists moved their attention to bombing high-capacity aircraft. The nature of the security problem is such that R&D may yield tools to reduce risk of given types, but a new threat is likely to crop up elsewhere. Defining a security threat as one would the risk of engine failure is not possible—it constantly changes as political winds shift and deterrence efforts force terrorists or criminals to think up new ways of doing harm.

As a result, the federal aviation security R&D effort is evolving toward an integrated system of threat detection and mitigation methods. The scope of the FAA's program has changed dramatically in the 1990s, expanding beyond a concentration in weapons and explosives detection technology test and evaluation to a broader R&D effort-one that includes human factors, hardening aircraft to sabotage, and security system integration.

Capacity and Air Traffic Management

Despite increases in scheduled airline traffic (see figure 3-6), FAA-measured delays[19] on flights through the busiest airports decreased over 40 percent between 1988 and 1992.[20] With the current reporting system, however, FAA is unable to estimate the total amount of delay experienced by airlines and other users of the air traffic control

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[17] *Bubble* refers to a specific portion of the atmosphere surrounding one or more airports.

[18] Bryson, op. Cit., footnote 15.

[19] Based on 1993 data from the FAA Office of Air Traffic System Management, NAS Analysis Program, OTA calculated that the number of operations delayed per thousand operations dropped 44 percent.

[20] Total operations at airports with FAA-operated air traffic control towers have remained steady in the late 1980s and early 1990s, in large part due to declining general aviation operations.

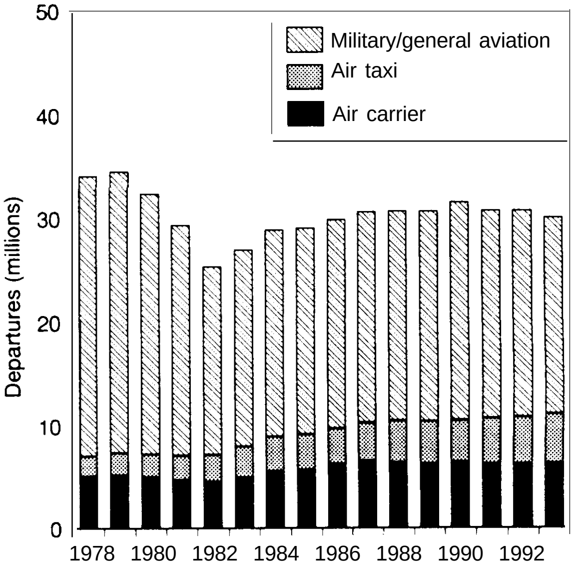
(ATC) system, nor can the agency precisely determine the cause of the delays.[21] Changes in airline scheduling practices in response to the Department of Transportation (DOT) publication of delay data further undermine trend analysis.[22] In short, what is known about delay is limited, and this lack of information affects both the planning and operation of the ATC system.

In addition, the area in which managing and fielding the results of aviation R&D has been most troublesome is capacity and delay. The focus of this R&D effort has been on tools to increase the efficiency of the ATC system in the face of increasing constraints on airport construction or expansion. Despite the availability of innovative technologies, new ATC systems implementation has been stymied from lengthy development cycles and reluctance on the part of controllers to accept some new products (see discussion of implementation issues in chapter 2).

As a result, the process of controlling (i.e., maintaining separation between) aircraft has changed little in decades, perpetuating costly inefficiencies. With the current ground-based surveillance system, aircraft fly from ATC sector to sector at select altitudes; route optimization for fuel consumption and minimum time is rarely facilitated. Over the oceans, beyond the range of radar surveillance, separations between aircraft are even greater and user-preferred routing nearly impossible to obtain.

The flight management capabilities of new aircraft greatly surpass those of ground infrastructure, which cannot support their use.[23] Some ATC automation has been introduced to help maximize the arrival and departure rates at airports, but no data have been assembled to assess any changes in performance.[24] Airspace and airfield capacity remains open to enhancement through new management methods and supporting technologies. Essential to the latter's development are models of the National Airspace System (NAS) and its major elements (see later section on Delay and Air Traffic Analysis). In addition, reliable, timely weather data are required, along with effective means of disseminating this and other information. Many of the advances proposed for the ATC system hinge on this capability.

FIGURE 3-6: U.S. Air Traffic Activity, FY 1978-93



NOTE Departures calculated from operations at airports with FAA-operated control towers

SOURCE Office of Technology Assessment, 1994, based on data from the FAA Office of Aviation Policy, Plans, and Management Analysis

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[21] FAA delay data reflect only delays of 15 minutes or more in any flight segment (i.e., takeoff, en route, or arrival) experienced by aircraft under FAA control. This reporting method precludes identification of all delays in system (see data and analysis section).

[22] John J. Fearnsides, General Manager and Senior Vice President, The Mitre Corp., personal communication, Apr. 19, 1994.

[23] For example the automated flight management systems onboard aircraft permit "four-dimensional" flight planning, but this advanced programming of aircraft position at a given time does not mesh with FAA's arrival queuing methods.

[24] See U.S. Congress, General Accounting Office, *Air Traffic Control: Justifications for Capital Investments Need Strengthening GAO/* RCED-93-55 (Washington, DC: U.S. Government Printing Office, January 1993), pp. 9-11.

TABLE 3-2: Major U.S. Aviation Database

Safety				
Accidents	Accident Investigation database	NTSB accident database	Manufacturers	
Incidents	Near mid-air collisions	Pilot deviations	Operational errors	Runway incursions
Inspection	Service Difficulty Reporting System (SDRS)	Safety Performance Analysis System (SPAS)	Program Tracking and Reporting Subsystem (PTRS)	
Other	NASA Aviation Safety Reporting System	System Indicators Program	RSPA database	DOD Air Carrier Analysis System
Capacity and air traffic management				
Delay	Air Traffic Operations Management System (ATOMS)[a]	DOT Airline Service Quality Performance (ASQP)	Consolidated Operations and Delay Analysis System (CODAS)	
Capacity mode/s	SIMMOD (trademark name for airport and airspace simulation model)	National Airspace System Performance Analysis Capability (NASPAC)		
Pavement wear	National Airport Pavement Registration and Demonstration Program			
Environment				
Noise	**National** Noise Impact Model (NANIM)	Integrated Noise Model (INM)		
Emissions/air quality	Aircraft Engine Emissions Database (FAEED)	FAA/USAF Emissions and Dispersion Model (EDM)	EPA emissions inventories	

[a] ATOMS stores flight and delay data retrieved from the Operational Performance System Network (OPSNET)

KEY NTSB = National Transportation Safety Board, RSPA = DOT's Research and Special Programs Administration; USAF = U S Air Force

NOTE All databases or sources belong to FAA unless otherwise noted

SOURCE Office of Technology Assessment, 1994

WEIGHING CURRENT ISSUES

This section relies on operational federal aviation databases, summarized in table 3-2, to illustrate what is known about the areas of greatest risk, least efficiency, or highest cost for the air transportation system. A more detailed discussion of the databases and analytical tools follows later in this chapter.

Safety and Security

The aggregate accident data show safety has improved dramatically since the introduction of commercial airlines (see figure 3-1, again). However, there are varying levels of safety (i.e., numbers of accidents and fatalities) for air carrier and general aviation operations (see table 3-3). For example, while the general aviation fatal accident rate declined almost 25 percent between 1982 and 1992, the rate and total number of fatalities remain high compared with the other aviation categories. Part 121 aircraft, while having the fewest accidents, on average experience the second largest number of fatalities. Aircraft operations data reveal that large commercial jets carry about 94 percent of all passengers and account for about 99 percent of passenger-miles.[25] Reducing the risk Of

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[25] Data for scheduled Part 121 carriers. U.S. Department of Transportation, Federal Aviation Administration, *FAA Statistical Handbook of Aviation* (Washington, DC: 1991), p. 5-15.

TABLE 3-3: U.S. Aviation Accidents and Fatalities by Industry Segment, 1978-93[a]

	Major airlines	Commuter	Air taxi	General aviation[b]
Total accidents	**387**	**428**	**2,026**	**45,320**
Fatal accidents	69	108	497	8,329
Total fatalities	1,948	558	1,199	16,048

~ 1993 data preliminary

b) US .*registered* civil aircraft not operated under 14 CFR 121 or 14 CFR 135

SOURCE Office of Technology Assessment, based on January 1989 and January 1994 National Transportation Safety Board data

fatalities aboard large air transports therefore minimizes the safety threat for the greatest share of the traveling public.

Relative to other transportation modes, however. aviation is an extremely safe industry. In 1992, highway-related deaths accounted for 94 percent of all transportation fatalities. Aviation fatalities numbered 1,103, or less than 3 percent of the total. General aviation and airlines experienced 874 and 33 fatalities, respectively.[26]

A small number of air carrier accidents are not survivable due to the extreme forces of impact.[27] Fatality rates in the remainder can potentially be reduced through implementation of advanced fire safety and crashworthiness technologies. Thus, a two-pronged safety effort is required: 1) preventing or reducing the chance an accident will occur in the first place, and 2) mitigating the effects. In order to derive possible solutions through operational and/or technology solutions, the primary and contributing causes of the accidents must be identified. The National Transportation Safety Board (NTSB) has primary responsibility for this ongoing effort.

Overall, the federal R&D programs directed at air transportation problems have had mixed success—the best results were obtained in areas where the problem was well characterized and the objectives clearly defined. Successful safety examples include reductions in the fire-related death rate among cabin occupants, mid-air collisions, and controlled flight into terrain. In addition, noise, engine emissions, and fuel consumption were reduced at the same time engines became more powerful and reliable.

OTA reviewed NTSB Part 121 accident briefs for the years 1985 through 1992 and found that human error (i.e., by pilots and other personnel) was an initiating factor in nearly 60 percent of total accidents.[28] Aircraft or component failure was the second-most frequent initiating factor; hazardous weather and other miscellaneous factors precipitated the remainder of the accidents evaluated (see table 3-4). A review of NTSB broad cause/factor assignments for all Part 121 accidents from 1975 through 1989 showed that rates for accidents related to aircraft malfunction or failure were nearly constant during this period: OTA noted several of

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[26] National Transportation Safety Board, “Transportation Deaths Drop 4.9 Percent in 1992,” SB 93-16, press release, July 1, 1993. Also see U.S. Congress, General Accounting Office, “Transportation Safety: Opportunities for Enhancing Safety Across Modes,” testimony at hearings before the House Committee on Public Works and Transportation, Subcommittee on investigation and Oversight, Feb. 10, 1994.

[27] Gellman Research Associates, Inc., “Benefit Estimates of the FAA's Aircraft Safety Research Program: 1992-2001 ,“ prepared for the Federal Aviation Administration, July 10, 1992. Gellman figures for years 1964 to 1988 showed that 12 of 624 accidents (2 percent) were nonsurvivable.

[28] For this review, OTA identified the two most significant sequential causal events for each accident. Initiating causal factor is not the same as first occurrence; e.g., a passenger's refusal to obey seat belt signs after the likelihood of severe turbulence was announced-not the presence of weather-related turbulence—would be the initiating factor should he or she be injured in a subsequent bounce. Weather would be included in a tally of all causal factors.

TABLE 3-4: Part 121 Total Accidents, 1985-92

	Scheduled passenger	Scheduled cargo	Nonscheduled passenger	Nonscheduled cargo	Total	Total[a] (by percent)
Initiating causal factor						
Pilot	45	16	1	5	67	41%
ATC personnel	5	0	0	0	5	3
Other personnel	19	1	0	2	22	14
Weather	27	0	0	0	27	17
Aircraft/component	**30**	3	1	4	38	23
Miscellaneous[b]	**4**	0	0	0	4	3
All causal factors						
Pilot	52	16	1	8	77	47
ATC personnel	10	2	0	0	12	7
Other personnel	24	***3***	1	2	***30***	18
Weather	53	4	0	2	59	36
Aircraft/component	31	3	1	6	41	25
Miscellaneous	4	0	0	0	4	3
Total accidents	130	20	2	11	163	

a Sum of percentages of initiating causal factors do not total 100 percent due to rounding For all causal factors, numbers do not total 100 percent because most accidents revolve multiple causes

b Miscellaneous Comprised of two birdstrikes, one unauthorized evacuation, and runway collision with pedestrian

NOTE Part 121 refers to airline operations using aircraft having 30 or more seats or payload capacity greater than 7,500 pounds The category does not Include air taxis or general aviation, nor typically commuter airlines Accidents involving sabotage or non-operational events are not included

SOURCE Office of Technology Assessment, 1994, based on National Transportation Safety Board data

these were linked to human error or poor management policies.[29] The data also showed a drop in weather-related causal rates (see figure 3-7).

Fire occurred in 37 of these accidents (28 percent). Of the four fires that occurred in flight, only one, an engine fire, was the initiating cause of the accident; none developed in the cabin. In 41 of the 130 accidents. weather-related or clear air turbulence was a factor: one fatal and 57 serious injuries to passengers and crew occurred but, typically, little or no aircraft damage.[30] In a dozen cases, serious injuries occurred during precautionary evacuations.

Over this same eight-year period, a total of 33 fatal accidents occurred involving U.S. cargo and passenger carriers.[31] Table 3-5 shows the breakdown of initiating and all significant causal factors for the 31 accidents for which NTSB had provided accident briefs.

Despite the high number of fatalities (148) associated with two recent controlled flight into terrain (CFIT) accidents,[32] fatal accidents caused

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[29] Examples of the latter include inadequate surveillance of operations by FAA and the failure of operators or companies to follow maintenance and inspection guidance.

[30] OTA found that human error, on the part of pilots, flight attendants, or passengers, was the initiating factor in almost 40 percent of the accidents involving turbulence. The one fatality, in 1990, stemmed from a combination of errors: the pilot flew through the overhang of a thunderstorm, contrary to company procedures; the flight attendants failed to enforce the seat belt instructions; and the passenger did not comply with the instructions.

[31] Included in this total are two accidents for which NTSB did not determine probable cause. Both accidents, involving controlled flight into terrain, occurred outside the United States; NTSB was not required to participate in the investigation. Not included were four security incidents that resulted in fatalities.

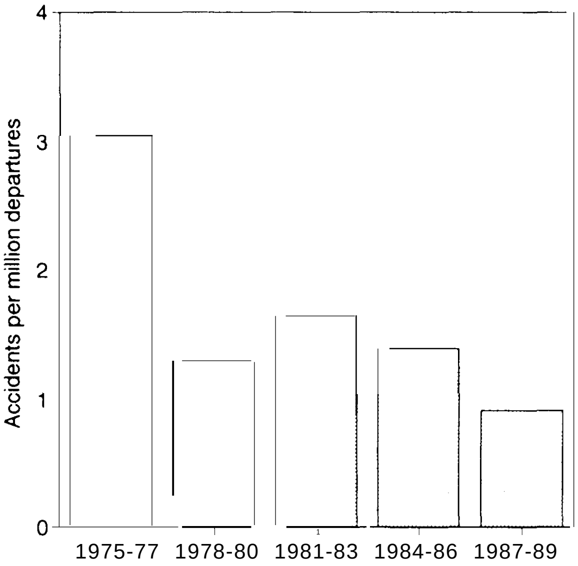
[32] Both accidents occurred in February 1989. The first, involving a charter passenger flight, took place in the Azores, Portugal. The second CFIT-related accident occurred in Kuala Lumpur, Malaysia, during a scheduled cargo flight.

by CFIT have decreased significantly since ground proximity warning systems were introduced onto large U.S. carriers in the mid-1970s. Based on this success, commuter aircraft are to be equipped by April 1994.[33] A recurring problem has been that some pilots, annoyed by prior false alarms, have turned off or ignored the system. Investigators suspect that this occurred in one of the most recent accidents.[34] Latest generation warning equipment presents far less of a false alarm problem, but proper pilot training is still required.

Loss of control related to aircraft malfunction or weather has been the primary factor in other accidents with high fatalities. Also, while runway incursions and collisions on the airport surface typically effect little damage or injury, the potential for catastrophic loss of life remains—recall the Tenerife collision and the 1991 accident at the Los Angeles International Airport involving an air transport and commuter aircraft. One of the most frightening images of aviation accidents is the mid-air collision. The last mid-air collision involving a large civil air transport over the United States occurred in 1986.[35]

The threat of an aircraft and its contents being quickly consumed by fire is equally horrifying. OTA estimates that approximately 13 percent of total fatalities in accidents involving U.S. commercial carriers during this period were due to fire.[36] This is down from earlier FAA estimates, using data from the 1960s through the 1970s, indicating that 15 to 20 percent of total fatalities was due to fire.[37] At about that same time, FAA estimated that 40 percent of fatalities in survivable accidents (e.g., where the fatalities from an accident in which no one could survive the forces of

FIGURE 3-7: Trend in Part 121 Accidents With Weather as a Factor, 1975-89



NOTE 1989 data were the last analyzed by the National Transportation Safety Board as of 1993

SOURCE Office of Technology Assessment, 1994, based on National Transportation Safety Board data

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[33] 57 *Federal Register* 9951 (Mar. 20, 1992).

[34] Don Nelson Senior Engineer, Boeing Airplane Safety, personal Communication, Nov. 1, 1993. Worldwide, not all aircraft have been equipped with ground proximity warning systems. ICAO reports that 638 people were killed in 1992 in 26 CFIT accidents, which include two crashes of Airbus aircraft at Katmandu, Nepal. "Briefs," *Traffic World,* Jan. 4, 1993, p. 23.

[35] The accident involved the collision of an Aeromexico aircraft and a general aviation aircraft; the collision took place over Cerritos, California. There have been several mid-air collisions involving commuter aircraft, but the last one involving a major scheduled U.S. carrier in U.S. airspace happened in 1978 over San Diego (Pacific Southwest Airlines). Wanda Glenn, National Transportation Safety Board, personal communication, July 29, 1994.

[36] The General Accounting Office cited 140 fire-related fatalities for the period 1985 through 1991; in 1992, none of the 31 fatalities was caused by fire or its effects. Total fatalities for the period 1985 through 1992, excluding deaths due to criminal or terrorist acts, numbered 1,049. National Transportation Safety Board, press release, Jan. 15, 1993; and U.S. Congress, General Accounting Office, *Aviation Safety: Slow Progress in Making Aircraft Cabin Interiors Fireproof,* GAO,' RCED-93-37 (Washington. DC: U.S. Government Printing Office, January 1993), p. 11.

[37] Constantine Sarkos, Manager, Fire Safety Branch, FAA Technical Center, personal communication, May 11, 1994.

TABLE 3-5: Part 121 Fatal Accidents, 1985-92

	Scheduled passenger	Scheduled cargo	Nonscheduled passenger	Nonscheduled cargo	Total	Total[a] (by percent)
Initiating causal factor						
Pilot	10	5	1	3	19	61 %
ATC personnel	2	0	0	0	2	7
Other personnel	2	1	0	0	3	10
Weather	1	0	0	0	1	3
Aircraft/component	4	1	0	0	5	16
Miscellaneous[b]	1	0	0	0	1	3
All causal factors						
Pilot	11	5	1	3	20	65
ATC personnel	4	0	0	0	4	13
Other personnel	10	1	1	0	12	39
Weather	5	1	0	1	7	23
Aircraft/component	4	1	0	0	5	16
Miscellaneous	1	0	0	0	1	3
Total accidents	20	7	1	3	31	

[a] Sum of percentages of initiating causal factors may not total 100 percent due to rounding For all causal factors, numbers do not total 100 Percent because most accidents revolve multiple causes

[b] Miscellaneous comprised of runway collision with Pedestrian

NOTE Part 121 refers to airline operations using aircraft having 30 or more seats or payload capacity greater than 7,500 pounds. The category does not include air taxis or general aviation, nor typically commuter airlines Accidents involving sabotage or non-operational events are not Included

SOURCE Office of Technology Assessment, 1994, based on National Transportation Safety Board data

impact are excluded) were fire-related.[38] Neither FAA nor NTSB has more recently published data on this percentage.

In addition to the hazard of accidental injury, fatality, or damage to aircraft, the possibility of intentional harm requires FAA and the industry to preclude the introduction of weapons or explosives aboard aircraft.[39] Figure 3-8 shows the escalation in terrorist threat to aircraft since the 1950s. Although the hijacking threat diminished in the 1980s, high-capacity aircraft became a favorite target of terrorist bombs, expanding the death toll and galvanizing public attention to the problem of aviation security (see box 3-1). Worldwide, the number of persons killed by bombings in general between 1980 and 1989 was approximately 1 ,020.[40]

Three catastrophic acts of sabotage involving U.S. airlines have occurred since the early 1970s. The estimated cost of the 1988 Pan Am bombing ranges between $411 million and $520 million.[41] According to FAA, the estimated direct cost of another such incident is $600 million—$150 million for the wide-body aircraft and $450 million for passenger lives.[42]

As access control and screening measures become more stringent, the threat of large amounts of common explosives being placed aboard air-

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[38] Ibid.

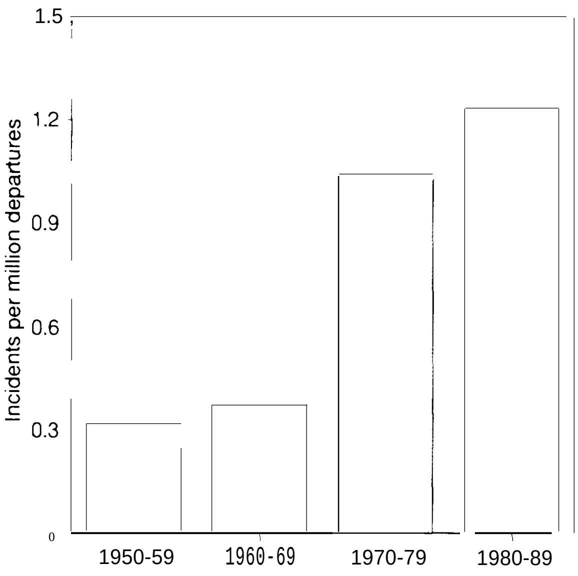
[39] Hostage-taking, aircraft Piracy and hijacking, sabotage, and indiscriminate bombings and shootings are examples of the many risks.

[40] Stefanie Stauffer, Manager, Strategic Intelligence Division, FAA Office of Aviation Security Intelligence, personal communication, May 29, 1994.

[41] 54 *Federal Register* 28987 (July 10, 1989).

[42] see U.S. Department of Transportation, Federal Aviation Administration, *The 1993 Federal Aviation Administration Plan for Research, Engineering and Development* (Washington, DC: February 1994), p. 7-1.

FIGURE 3-8: International Aircraft Security Incidents



SOURCE Office of Technology Assessment 1994 based on 1993 FAA data

craft or in airports is reduced. However, new types of explosives may be introduced that can more easily elude detection: in addition, another type of risk has arisen—more than 100 countries possess some version of shoulder-launched heat-seeking missiles.[43]

Comparing R&D Funding to Risk

Table 3-6 shows the categories of accident types or factors and the applicable FAA R&D program area, along with the percentage of fatal accidents, fatalities, and program funding. For the period 1985 to 1992, the two most prevalent factors in fatal airline accidents were human error and fire: security was third.

When fatalities are considered, however, another ranking emerges. While human error was again predominant, comparable percentages of fatalities were attributed to security incidents and factors FAA includes in its Flight Safety R&D program area (i.e., ground icing, encounters with hazardous weather, and CFIT). The smallest share of fatalities was related to structural failures.

BOX 3-1: Recent Significant Terrorist Incidents in Aviation

1982	Mid-air explosion on a Pan Am jet bound for Hawaii from Tokyo, killing a Japanese boy and injuring 15 other passengers
1985	Hijacking of TWA Flight 847 by Shi'ite terrorists, lasting 17 days, with the torture and killing of a U S Navy diver
1986	Hijacking of Pan Am Flight 73 in Karachi, killing two U S citizens Bombing of TWA Flight 840 en route from Rome to Athens, killing four Americans
1988	Destruction of Pan Am Flight 103 over Lockerbie, Scotland, by an onboard explosive device, killing 271 people in the aircraft and on the ground

NOTE In 1987 a Catastrophic nonterrorist security incident occurred a recently dismissed Pacific Southwest Airlines (PSA) employee boarded a PSA flight and, en route shot the pilot and copilot The plane crashed as a result killing all 43 passengers and crew aboard

SOURCE U S Congress Office of Technology Assessment *Technology Against Terrorism Structuring Security* OTA-ISC-511 (Washington DC U S Government Printing Office, January 1992) pp 24-25

As shown in table 3-6, the greatest share of FAA's safety-related Research, Engineering and Development (RE&D) budget in fiscal year 1994 (33 percent) is directed at security. Nearly 21 percent of the 1994 RE&D budget is directed at aging aircraft, although the risk of fatality is minimal compared with that associated with human error, which receives 25 percent. These figures indicate that funding does not correlate with such measures of the safety problem.

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[43] Philip J Klass, "Hardened Containers Under Development," *Aviation Week & Space Technology*, Nov. 23, 1993, *pp.* 90-91. Also see Marvin B. Schaffer, "Concerns About Terrorists With Manportable SAMS," RAND P-7833, paper prepared for the Transport Aircraft Survivability Symposium and Exhibition Session on "New and/or Unique Threat Challenges," " St. Louis, MO, Oct. 12-21, 1993.

TABLE 3-6 Comparison of Fatal Accidents and Related FAA Safety R&D Expenditures

Accident factor	Percent of fatal accidents	Percent of fatalities	FAA RE&D Program	Percent of total budget[b]
Security	11%	28%	Systems Security	**33%**
Human factors[c d]	75	60	Human Factors and Aviation Medicine	25
Structural				
Aging **aircraft**	3	<1	**Aging Aircraft**	21
Other airframe failure or malfunction	6	<1	**Crashworthiness/Structural Airworthiness**	4
Subtotal	9	1		25
Engine or fuel system				
Propulsion and **fuel system reliability**	3	3	**Propulsion and Fuel Systems**	3
Catastrophic engine failure	3	*10*	**Catastrophic Failure Prevention**	3
Subtotal.	6	12		5
Flight safety hazards				
Icing, snow	**11**	5	**Flight Safety/Atmospheric Hazards and Weather**	**5**
Other weather	**8**	*14*		
Controlled flight into terrain	**6**	**13**		
Subtotal.	25	32		5
Fire[d,e] -			Aircraft Systems Fire Safety	5
In-flight fire	3	**0**		
On-ground fire	47	12		
Surface collisions	14	4	Airport Safety Technology	3

[a] percent of 36 fatal accidents and sabotage events for Part 121 aircraft from 1985 to 1992 (excludes 1990 collision with pedestrian on runwaY) Total fatalities were 1,146

[b] Total FAA safety/security R&D funds requested for fiscal year 1994 were $109 2 million

[c] Loss of control or use of Improper procedures—not including controlled flight Into terrain

[d] Some accidents counted twice

[e] National Transportation Safety Board, press release, Jan 15, 1993, and U S Congress, General Accounting Office, *Aviation Safety Slow Progress in Making Aircraft Cabin Interiors Fireproof*, GAO/RCED-93-37 (Washington, DC U S Government Printing Off Ice, January 1993)

NOTE Percentages may not add due to rounding

SOURCE Office of Technology Assessment, 1994, based on Boeing and National Transportation Safety Board data

However, safety and security R&D budget allocations cannot be decided based on U.S. fatality or fatal accident rates alone. Major accidents involving non-U.S. carriers help to focus FAA's attention, as does security intelligence. In addition, economic and other factors contribute to the potential escalation of some hazards.

In 1990, roughly 46 percent of the U.S. commercial air transport fleet was over 15 years old, and 26 percent was over 20 years old.[44] The number of aircraft with more than 20 years of service life is expected to double by 2000; given this, it is possible that the aging aircraft problem will become more significant. Similarly, although the number of deaths related to terrorism and criminal acts averages less than accidental fatalities, security threats could be expected to increase greatly in the absence of a visible, active deterrence effort (which includes R&D to derive methods to minimize the risk). Of course, another problematic task is deciding the level of investment for security program elements, for example, explosives detection, aircraft hardening, or passenger profiling.

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[44] National Aeronautics and Space Administration, Office of Aeronautics, "Advanced Subsonic Technology Program: Program Summary," February 1994, p. 8.

Besides the possibility of risk escalation, other factors to consider are:

- existing operational or technological options, even if economically unfavorable:
- secondary effects of possible solutions on other problems; and
- timing of realized benefits, improvements, and the longevity of solution.

Existing Options

Often, several options exist to address current problems, even though some may be uneconomical. Fatal icing-related airline accidents in 1982, 1987, and again in March 1992 spurred the development of new ground deicing procedures, including wider use of a longer lasting anti-icing fluid. However, rather than the lack of deicing technologies, pressure to keep to schedules and perhaps some pilot hubris were the primary factors in takeoff accidents; closer scrutiny of the aircraft's control surfaces and application (or reapplication) of existing deicing fluids was needed.

Options for reducing the risk of structural fatigue-related accidents include improved maintenance oversight, less time-consuming and more effective inspection technologies, and design changes. Enhanced scientific understanding of aging aircraft phenomena is a prerequisite. Other examples of accident prevention options include more thorough visual screening of passengers and baggage, and holding aircraft on the ground in bad weather. Each would exact huge costs.

Detecting and predicting hazardous weather are benefiting from steady, if relatively little, R&D attention and a recent confluence of improved communications and display technologies and advanced sensor and analysis tools. As a result, enhanced situation awareness for pilots and improved air traffic management capabilities are feasible; OTA notes this is one area where additional dollars might accelerate benefits across several missions (e.g.. the savings resulting from reduced delay, increased safety, and reduced flight times, fuel use, and engine emissions).[45] The capacity implications and weather R&D and paucity of long-term weather research are discussed further below.

On the other hand, steady attention to the role of human factors in causing accidents has not reduced its prevalence. Its constancy suggests there is no "silver bullet" solution to the multidimensional human factors problem in aviation. Another suggestion is that automation introduced to relieve workload has only shifted problems from one phase of activity to another. Quantitative evaluation methods are needed; therefore, further R&D on human performance issues in the aircraft, the control tower, and on the ground will be required.

Much of FAA accident mitigation R&D focuses on improving fire safety. Developing titanium hulls, for example. is a feasible but inordinately expensive method of reducing the hazard of burn-through during postcrash fires. Despite the relatively few number of fatalities caused by fire in recent years, if further improving fire safety is desired, additional R&D will be required to devise ways of speeding safe evacuation from aircraft cabins or better detecting and suppressing fire development. For example, if ultra-fire-resistant materials alone are expected to *increase* cabin survivability times, then more research into the mechanisms of fire development is needed (see chapter 4). Changing passenger demographics suggest further fireproofing of the cabin and fuselage would be more beneficial than attempting to increase average evacuation rate. The mean time required for leaving one's seat, moving down an aisle, and exiting through emergency doors tends to be greater for older passengers; the continued aging of the flying public, along with increased flights by persons with disabilities, make it un-

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[45] OTA also notes the possibility of technology spinoff for avoiding clear air turbulence and the seemingly intractable wake vortex-related problem of safely reducing separations between aircraft.

likely that overall evacuation times can be reduced without radical (and costly) changes to cabin configurations.[46]

Secondary Effects

Because considerable progress has already been made toward achieving an extremely safe aviation system, any technological or procedural "improvement" may also have unintended, negative side-effects. Examples include the overall effect on pilot workload from the introduction of automation in the cockpit and the wide variety of complex avionics with which mechanics must familiarize themselves.

"Risk/risk" analyses of technology or regulatory decisions are increasingly valuable for illuminating the interactive effects of changes to the system. The results are sometimes controversial, especially when they prevent a safety initiative. For example, FAA concluded in the late 1980s that using portable breathing equipment (PBE) in transport aircraft emergencies could result in more deaths, rather than fewer, and support for mandating passenger PBE onboard commercial aircraft diminished.[47]

Timing of Costs and Realized Benefits

Another factor to be weighed in selecting areas of applied R&D is the length of time required to realize benefits from development efforts (just as the impact of attempting to accelerate implementation of new designs or components must be considered in imposing regulatory requirements). For example, should new materials be developed to augment an aircraft hull's resistance to explosion or fire, the costs of retrofitting entire fleets preclude their immediate introduction. While effective near-term enhancement to cabin safety is possible with speedier installation of new seat designs and interior materials technology, the costs are substantial and, when compared with the economic value of lives saved, the effort is not cost-effective.[48]

Over the long term, though, there are many potential safety and security enhancements that could be attained for new generations of aircraft and the future air traffic management system. These include enhanced situation awareness, improved selection and training methods for airline and FAA personnel, aviation weather "nowcasts," fire-proofed cabins, and airframes hardened against explosives of minimal strengths (all described in the subsequent chapter on crosscutting research and innovative technologies).

Capacity and Traffic Management

FAA's delay data show that, while the number and cumulative amount of delays have decreased in previous years, congestion remains a problem at many major airports. Using 20,000 hours of annual aircraft delay as the indicator of congestion, FAA identified 23 airports as congested in 1991.[49] FAA data indicated that approximately one-third of delays resulted from peak demands that exceeded the capacity of ATC and runways.[50] Bad weather was a factor in approximately two-thirds

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[46] See Office of Technology Assessment, op. cit., footnote 4, ch. 2; and J.G. Blethrow et al., Civil Aeromedical Institute, *The Emergency Escape of Handicapped Air Travelers, FAA-AM-77- 11* (Washington, DC: Federal Aviation Administration, July 1977).

[47] FAA found that, while devices such as smokehoods would reduce passenger incapacitation from toxic fumes during a fire, *donning the* hoods would lengthen the time it takes to evacuate the aircraft, the most critical factor in postcrash survivability. See E.A. Higgins, *Summary Report the History and Events Per* (Washington, DC: U.S. Department of Transportation, Federal Aviation Administration, June 1987); and Garnet A. McLean et al., *The Effects of Wearing Passenger Protective Breathing Equipment on Evacuation Time Through Type III and Type IV Emergency Aircraft Exits in Clear Air and Smoke,* Final Report, DOT/ FA.4 AM-89/ 12 (Washington, DC: U.S. Department of Transportation, November 1989).

[48] See General Accounting Office, op. cit., footnote 36.

[49] Frank Soloninka Office of System Capacity and Requirements, Federal Aviation Administration, personal communication, May 19, 1993.

[50] U S Department of Transportation, Federal Aviation Administration, *1993 Aviation System Capacity Plan*, DOT/ FAA/ASC-93-] (Washington, DC: 1993), p. I -15.

of reported delays—largely because corresponding instrument flight rules, although in effect less than 10 percent of the time, require greater separation between aircraft in controlled airspace. This contrasts greatly with the situation in Europe, where ATC and airports account for nearly two-thirds of delay and bad weather for much less than one-third.[51]

Other measures of capacity (i.e., airspace efficiency and flexibility) include traffic volume and rate and deviations from preferred routes, and the resulting extra fuel and maintenance penalty. In general, airlines desire routes optimized for distance and favorable winds in order to reduce crew time and maintenance costs and to minimize fuel consumption. The current ATC system rarely can accommodate user-preferred routes. In addition, there is a fuel burn penalty for flying extra distances around storms; more accurate weather data could be used to optimize paths.

For air carriers, the impact of insufficient airport or en route capacity is measured in additional operating costs, including extra fuel required by inefficient routing, and passenger time due to delays. According to the Air Transport Association, member airlines are losing $3.5 billion per year because of ATC system limitations.[52]

Because of political and economic factors, it is increasingly difficult to derive additional system capacity from new airport construction or expansion. New technology is expected to provide a small fraction of the capacity needed to meet projected demand in coming years (see figure 3-9); other alternatives will be essential to making up some of the shortfall.[53] However, measurable, near-term improvements are achievable.

Long spacings between aircraft on approach and takeoff, designed to mitigate the hazard posed by wingtip vortices, exacerbate capacity constraints in the terminal area

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Innovative technology will permit reduced longitudinal separation standards and spacing between aircraft approaching multiple runways, key sources of additional capacity (see table 3-7). Models of the National Airspace System. including new simulation capabilities, help FAA to evaluate the interaction of new air traffic management procedures and their net effect on system performance. The performance of these systems depends greatly on aircraft and ATC capabilities, whose basic components are described in chapter 4. Also, the ability to better monitor weather along flight routes will help pilots trim miles, and reduce fuel consumption, during detours around bad weather. Based on NASA tests of cockpit weather

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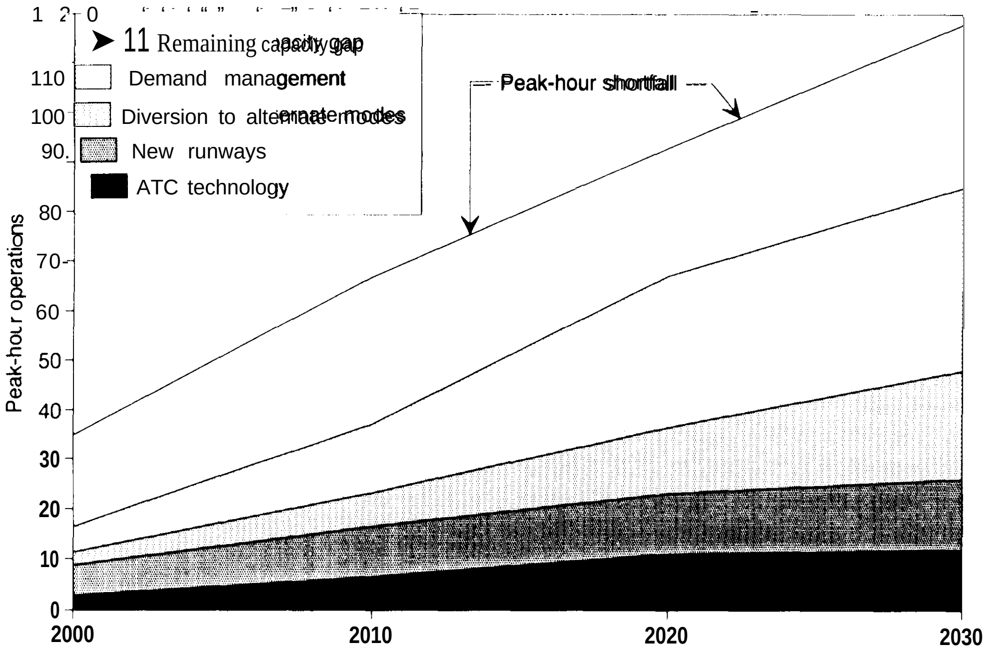
[51] David Henderson, Data Division, Association of European Airlines, personal communication, Mar. 15, 1994. The ATC delay stems in large part from the more prevalent use of instrument flight rules for governing European air traffic. Feamsides, op. cit., footnote 22.

[52] Air Transport Association of America, "Air Traffic Management in the Future Air Navigation System," white paper, June 16, 1994, p. 1.

[53] At least 80 percent of future demand must be addressed by options that are difficult to execute, e.g., demand management and alternative modes of transportation.

FIGURE 3-9: Options To Meet Projected Shortfall in Peak-Hour Capacity Level 1 Airports



SOURCE Apogee Research, 1992

display systems, the estimated savings in a typical airline's operating costs would be $5.9 million annually.[54]

However, many weather-related delays result from not being able to predict the start and end of instrument meteorological conditions. To illustrate the problem, FAA uses the hypothetical example of morning fog at Chicago's O'Hare International Airport that halves the potential acceptance rate for arrival traffic. If the fog lifts an hour earlier than forecast, the pipeline of traffic will not be filled quickly enough to regain normal acceptance rates until that hour expires, even if the ground hold is removed immediately. The inadequate weather information thus results in a loss of 50 percent of capacity for an hour; furthermore, the loss has a ripple effect throughout the national system.[55] This points to the need for ceiling and visibility forecasting methods.

Environment

Relative to other transportation modes, aviation pollutant emissions are small. However, the industry's energy efficiency, measured in energy use per passenger-mile, is higher than that of other modes. For example, the respective energy inten-

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[54] Charles H. Scanlon, NASA Langley Research Center, quoted in "'NASA Says Cockpit Weather Display Cuts Fuel Burn, Aids Safety,'' *Air Line Pilot*, December 1993, p. 45.

[55] U.S. Department of Transportation, Federal Aviation Administration, *Aviation System Capacity Annual Report* (Washington, DC: October 1993), p. 18.

TABLE 3-7: Potential Airport Capacity Enhancements

Parameter	Capacity increase (percent)	Comments
Visual flight rules		
ATC system Improvements	18 to 22[a]	Depends on whether operations are arrivals-only mixed (e. g., 50/50), or departures-only
Interarrival time variability	17 to 18	Arrivals-only operations—assumes 50 percent reduction in interarrival time variability. Negligible capacity Increase for mixed operations
Interarrival separation	7	Arrivals-only operations
Departure separation	3 to 18	Function of share of departures
Runway occupancy time	0 to 9	Reductions in other parameters have little or no effect on mixed operations unless there are corresponding reductions in runway occupancy time (mean and variability),
Instrument flight rules		
System variabilities	13 to 16	May be technologically difficult to achieve reductions in interarrival time variability.
Longitudinal separations	4 to 6	
Multiple-independent approaches	31 to 100[b]	Function of runway configurations
Separations for multiple-dependent approaches	25	Reduction in diagonal separation requirements
Runway occupancy time	—	Insignificant limitation in Instrument flight rules

[a] Potential capacity Increases are nonadditive and assume approximately 50-percent reduction in variabilities

[b] Instrument flight rules base capacity is 75 to 90 percent of visual flight rules base capacity for the *same* runway configuration However use of converging and multiple parallel runways is restricted under Instrument flight rules, Imposing a significant capacity penalty at many airports

SOURCE The Mitre Corporation, 1987 and 1994 data

sities for Part 121 aircraft and automobiles in 1990 were 4,811 and 3,739 Btu per passenger-mile.[56] While commercial aviation's energy efficiency has improved (see figure 3-10), the drive for energy efficiency continues because a significant portion of airline operating costs relate to fuel use,[57] and increased fuel use resulting from more operations or longer flights generates more emissions of combustion byproducts.[58] For some general aviation aircraft, replacement—not reduced use—of leaded aviation gasolines is being sought: small aircraft are the largest single source of airborne lead particles.

Reducing engine exhaust impacts, along with aircraft noise, requires further attention because: 1) U.S. and international communities will permit little or no backsliding even as the industry continues to grow; 2) there is a push for increased stringency; and 3) with existing technology, these improvements cannot be attained for the current

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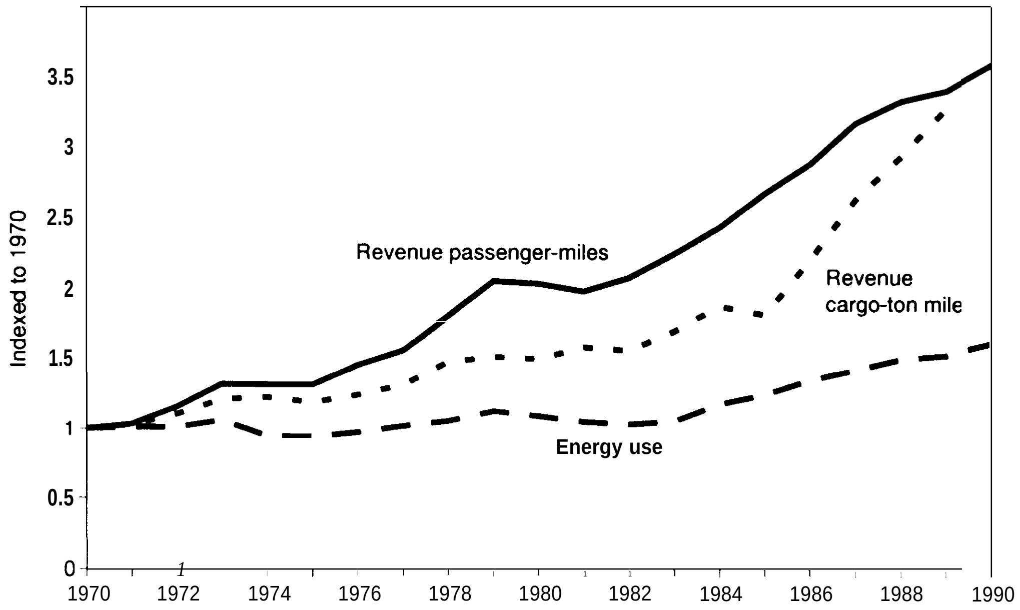
[56] See Center for Transportation Analysis, Energy Division, *Transportation Energy Data Book: Edition 13*, ORNL-6743 (Oak Ridge, TN: Oak Ridge National Laboratory, March 1993), table 2.13, p. 2-24.

[57] *According* to *Boeing,* for a typical aircraft, fuel expenses are roughly *50* percent of the cash direct operating costs (i.e., for fuel, flight crew, and maintenance), and 33 percent of all cash airplane-related operating costs. Calv in Watson, Boeing Commercial Airplane Group, personal communication, Aug. 17, 1994. Actual fuel costs depend heavily on world market price.

[58] In the Prior decade, e.g., aviation's share of the total U.S. demand for petroleum rose to 10.2 from 8.2 percent and fuel consumption rose 41 percent to 414 million barrels. Frank A. Smith, *Transportation in America, 10th* Ed. (Waldorf, MD: Eno Transportation Foundation, Inc., October 1992), pp. 56-57.

FIGURE 3-10: Energy Use, Passenger-Miles, and Cargo-Miles for Certificated Route Air Carriers, 1970-90



SOURCE Office of Technology Assessment, 1994, based on 1993 Energy Information Administration data

fleet. In addition, the scientific understanding of potential problems with high-altitude subsonic aircraft emissions is limited. Before an extensive effort to design improved combustors and evaluate their performance in terms of safety and cost-effectiveness is undertaken, increased knowledge of the effects of engine emissions on the atmosphere is needed.[59]

Where only scanty or inexact measures of the environmental effects are available, the indirect economic costs of environmental degradation are difficult to assess.[60] However, the direct cost to industry of compliance with emissions, noise, or stormwater runoff regulations can be more easily quantified. The Albany (New York) Airport, for example, spent over $13 million for a recovery and treatment system to preclude runoff from contaminating the local drinking water supply.[61] Aircraft modifications necessary to meet Stage 3 noise abatement requirements could mean spending $1.5 million to $3 million per aircraft for hushkits or $10 million to $12 million per aircraft for re-engining.[62]

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[59] Some of the ground-level impact can be derived from information contained in EPA databases, but data from the upp troposphere and stratosphere are missing.

[60] For example, the cost to society of increasing airport noise by 1 decibel is relative to the ambient noise level in a given neighborhood. Furthermore, even when the amount of pollution or other impact can be quantified, there is little agreement on how to calculate the costs of such impacts.

[61] "Airports Tackle Deicing *concerns,*" *Aviation Week & Space Technology,* Jan. 11, 1993, p. 43.

[62] Stanley W. Kandebo, "Hushkits Gain Favor in Poor Economy," *Aviation Week & Space Technology,* Nov. 23, 1992, p. 83.

Other examples of imposed costs are the impact of the mandated phase-out of leaded gasoline on general aviation fuel price and availability[63] and the pollution-reduction expenses incurred in areas of nonattainment with respect to air quality standards. Also, there are capacity constraints associated with noise, air-, and water-quality impacts. The aviation industry is capital-intensive with long development horizons. Because airports and aircraft have long lives, the timing and feasibility of environmental requirements are increasingly important.

In general, the impetus for environmental R&D typically comes less from concern over the impact on the environment (after all, it is often small compared with other sources) but from the potential effects environmental rulemaking has on air transportation. The major exceptions to this involve high-altitude atmospheric impacts from subsonic and supersonic civil aircraft.

The viability of a new generation of supersonic transports—the proposed high-speed civil transport (HSCT)—hinges on environmental compatibility (i.e., reducing any stratospheric ozone depletion caused by a large HSCT fleet to acceptable levels). This requires an extensive research effort in order to quantify the potential impact and evaluate possible control measures. NASA's work in this arena is described in chapter 4.

ISSUES IN SETTING PRIORITIES

There have been periodic attempts to revise FAA's R&D priorities and better define its capabilities. In recent years, Congress and the aviation community have urged greater emphasis on R&D that is directed at identifying or predicting problems and focusing on long-term issues. The General Accounting Office (GAO) has recommended that FAA develop a mechanism to track long-term or future-oriented research efforts; FAA is exploring ways to modify the RE&D information system and otherwise implement GAO's recommendation.[64]

Legislation enacted in 1988 and 1990[65] required FAA to expand its R&D focus specifically to include human factors, aging aircraft, catastrophic failure prevention, simulation, and security. Corresponding changes in program funding between 1988 and 1994 are shown in table 3-8. For fiscal year 1993, Congress appropriated $230 million to FAA for R&D. Roughly 45 percent of these funds went to projects related to system capacity, approximately 16 percent each to safety and security, and nearly 12 percent to human factors and aviation medicine.

TABLE 3-8: Effects of Aviation Safety Research Act on FAA R&D Spending ($ millions)

Mandated area	1988a	1991	1994[b]
Human factors and aviation medicine	$6 2	$17 2	27 3
Simulation modeling	0.8	9. 2[c]	11,8
Aircraft structured	1 7	17 6	26.8
Fire safety	3 5	4,3	5 7
Total	12.2	48.2	71 5

[a] Obligations

[b] Requested funding for fiscal year 1994

[c] Includes National Simulation Lab National Airspace System Performance Analysis Capability, simulation model and development and airspace system models

[d] Includes aging aircraft research

SOURCE Office of Technology Assessment, 1994, based on General Accounting Off Ice analysis of Federal Aviation Administration data

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[63] Sections 220 and 226 of the Clean Air Act Amendments of 1990, Public Law 101-549, Nov. 15, 1990, prohibit the manufacture or sale of new lead-burning engines after model year 1992 and the sale of leaded fuel for use in motor vehicles by 1996. Although general aviation aircraft were exempted from the former provision, general aviation advocates fear that the amendments will make it economically infeasible for fuel companies to continue to manufacture general aviation fuel in the interim. "Tough Times for the Little People," *Interavia Aerospace Review*, March 1991, pp. 31-32.

[64] Allen Li, Associate Director, Transportation Issues, Resources, Community, and Economic Development Division, U.S. General Accounting Office, testimony at hearings before the Senate Committee on Appropriations, Subcommittee on Transportation and Related Agencies, May 20, 1993, p. 7.

[65] Aviation Safely, Research Act of 1988, Public Law 100-591, Nov. 3, 1988; Catastrophic Failure prevention Act of 1990, Public Law 101-508, Nov. 5, 1990; and Aviation Security Improvement Act of 1990. Public Law 101-604, Nov. 18, 1990.

The 1988 Aviation Safety Research Act also mandated establishment of an advisory committee to assist FAA in evaluating its research effort. Comprised of experts drawn from all aspects of air transportation, the FAA Research, Engineering and Development Advisory Committee meets quarterly to discuss the status of individual R&D programs and their progress relative to agency objectives. Similarly, the 1990 Aviation Security Improvement Act directed the formation of the Aviation Security Research and Development Scientific Advisory Panel, constituted under the auspices of the committee.

In 1991, at the request of the FAA Administrator, the FAA RE&D Advisory Committee established a panel (often called the Augustine Panel)[66] to review FAA's plan for R&D. The panel found that ". . . no factor poses more severe potential limits of future air transportation than . . . system capacity."[67] The panel also stated that the application of new technology will be a large part of the solution to the air traffic saturation problem and recommended that FAA be provided with additional financial and human resources to accomplish its objectives. Other recommendations included strengthening FAA's systems engineering methodology, expediting funding and use of the national simulation capability, and giving increased attention to the application of space-based communications, navigation, and traffic surveillance system elements. The review panel also suggested that FAA adopt a matrix-based approach for comparing and quantifying the estimated contributions of individual research projects to FAA goals.[68]

However, a 1992 GAO assessment of the FAA RE&D plan found that the RE&D program alone could not achieve all the goals set out in the plan .69 GAO indicated that FAA could strengthen its plan by delineating staffing and resource requirements, and by incorporating the RE&D goals into the rest of the organization.

The Augustine Panel updated its recommendations in 1993, documenting the need for a concentrated effort in the FAA RE&D program to establish more specific goals to help the agency manage congestion problems (among other issues), and to present a coordinated program for consideration by the agency as a whole.[70]

In its 1992 assessment, GAO also recommended that FAA take this type of systems approach to its multifaceted mandate, citing a special relationship between developing specific ATC and security technologies and understanding how various technologies interact.[71] For example, an aircraft's ability to withstand a blast must be considered when developing requirements for explosives detection system designs. Understanding aircraft hardening limitations thus influences the operation of security screening systems.

I Cost-Benefit Analysis

To improve its methods of setting R&D priorities, FAA is also using cost-benefit analysis (CBA),

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66 Named for its Chairman, Norman Augustine.

67 FAA Research, Engineering and Development Advisory Committee, R&D Plan Review Panel, *Review of the FAA* Research, *Engineering and Development Program* (Washington, DC: November 199 I), p. 1.

68 ibid., pp. 1, 31-32, 36-38.

69 U.S. Congress, General Accounting of ffice, *Aviation* Research: *FAA Could* Enhance *Its Program To* Meet *Current and Future Challenges,* GAO/RCED-92-180 (Washington, DC: U.S. Government Printing Office, June 1992), p. 2.

70 Feamsides, op. cit., footnote 22. See FAA Research, Engineering and Development Advisory Committee, R&D Plan Review panel, *U.S. Leadership in Air Traffic Services: An Update of the Earlier Review of the FAA Research, Engineering and Development Program* (Washington, DC: January 1993).

71 Genera] Accounting office, op. cit., footnote 69, p.10.

which FAA successfully employed for the Capital Investment Plan (CIP) budgeting process.[72] (See box 3-2.) Paralleling the CIP effort, CBA for individual RE&D projects is used to support mission needs statements as part of a multiphase decision process similar to A- 109.[73] The projected benefits are based on the operational savings associated with the implementation of the systems and technologies that might be derived from the RE&D program.

According to a Volpe National Transportation Systems Center (VNTSC) assessment of ATC and capacity projects, the benefits to be realized from the RE&D program are: for FAA, increased controller and maintenance staff productivity and cost savings in operations; and for air carriers, reduced

BOX 3-2: Cost-Benefit Analysis at FAA

The Federal Aviation Administration's use of cost-benefit analysis (CBA) goes back at least to the 1970s Early examples include facility establishment criteria for control towers, airport surveillance radar, and Instrument landing systems The acquisition of major new systems, such as the upgraded third-generation ATC system, was evaluated with CBA.[1] When FAA formulated the Capital Investment Plan (CIP) In 1981, CBA continued as an Integral part of the process More recently, it has been applied to elements of FAA's Research, Engineering and Development program

The Office of Aviation Policy, Plans, and Management Analysis sets agency standards for CBA, performs regulatory analyses, and conducts CBA for terminal area facilities such as ATC towers and airport surveillance radar The Operations Research Service (AOR) performs analyses for facilities and equipment Investment projects contained in the CIP and for technological program-level decisions [2]

The Office of Management and Budget (OMB) requires major system acquisitions to have a CBA justification Specifically, this analysis supports the mission needs statement, which is the first phase of the OMB A-109 "Major System Acquisition Process. " AOR's work has several other applications in addition to supporting mission needs statements One application has been to develop the CIP baseline, a summation of the estimated benefits for all projects in the CIP AOR's analyses have also improved FAA program offices' understanding of CIP benefits Under contract to FAA, Martin Marietta Information Systems Group performs much of the analysis and data collection required for this effort Martin Marietta also maintains the database of results for each of the CIP projects

(continued)

[1] Carlton Wine, Manager Information Systems, FAA Office of Aviation Policy Plans and Management Analysis, personal communication June 17 1994

[2] Ibid

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[72] FAA's Office of Operations Research staff informed OTA, during personal communications, that the results of the analyses performed for the CIP have been used by FAA project offices, the FAA budget office, and by the Office of Management and Budget.

[73] FAA's Office of Operations Research manages this program with primary analytical support from DOT'S Volpe National Transportation Systems Center (VNTSC). Although VNTSC is responsible for an overall evaluation of the RE&D program, the FAA Technical Center manages the work for the aircraft safety, airport technology', and system security programs. For example, one recent effort at the Technical Center compared the potential benefits from different areas of aircraft safety research (flight safety, aging aircraft, structural safety, and aircraft systems fire safety).

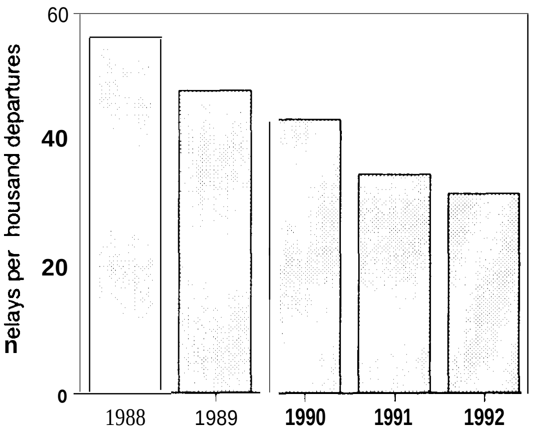
BOX 3-2: Cost-Benefit Analysis at FAA (Cont'd.)

Analytical Methodology

For the CIP, the two major categories of benefits are the cost savings for FAA and for aviation system users. FAA benefits Include personnel cost reduction resulting from increased air traffic controller productivity and reduced maintenance needs. AOR's analysis indicates that FAA will realize additional operational savings in nonlabor areas such as leased communications costs, rents, and utilities. User benefits consist of systemwide delay reductions, availability of more efficient routings, and the reduced risk of accidents. The first two of these benefits are quantified by counting the savings derived from decreased aircraft direct operating costs and passenger travel time. In determining costs, only future expenditures are included. Sunk costs (those amounts that have already been spent) are excluded from the analysis.

Reduction in Delays

The amount of time by which delays will be reduced is estimated by combining forecasts of the growth in air travel with forecasts of the length of delay per aircraft operation. However, FAA's long-term traffic forecast does not allow for the effect of airport congestion on traffic demand. Basing projections of flight delays on the difference between the unconstrained air traffic forecast and actual airport capacity, then, results in an overstatement of predicted delays. Air carrier operating practices would probably change if the cost of delays becomes prohibitive. For example, the use of larger aircraft might alleviate the peak-hour delays at the busiest airports.[3] In addition, community opposition to aircraft noise may reduce some of the forecast growth in aircraft operations. In fact, while FAA's airport delay forecasts have shown increasing congestion until recently, FAA's current data have shown reductions in delays (see figure). The estimate of the length of reduced delays forms the basis for 60 percent of total CIP benefits. Thus a significant portion of the CIP benefits projected by FAA are open to question.



Delays of 15 minutes or more at
55 major airports in the United States.

Passenger *Time Savings*

The value of passenger time savings represents the gain to travelers resulting from decreased time in the air and more reliable airline schedules. AOR's analysis uses a value recommended by FAA's Office of Aviation Policy, Plans, and Management Analysis,[4] However, because of the range of reported results, an estimate of the value of travel time for air travel cannot be considered an exact value.[5] Thus, the CIP benefits attributed to passenger time savings, which represent more than one-half of total benefits, should be recognized as Imprecise.

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[3] U S Congress, Office of Technology Assessment, New *Ways. Tiltrotor Aircraft and Magnetically Levitated Vehicles*, OTA-SET-507 (Washington DC. U S Government Printing Office, October 1991), p. 45

[4] The amount used is $4050 per hour Based on a review of theoretical and empirical studies This value represents a weighted average for both business and nonbusiness travel and for the different types of air travel (e g , domestic air carrier, International air carrier, commuter) In general, the value of travel time saved for business trips is the typical traveler's hourly earnings rate, for nonbusiness travel, it is 1 5 times the wage rate

[5] U S Department of Transportation, Federal Aviation Administration, *Economic Values for Evaluation of Federal Aviation Administration Investment* and Regulatory Programs (Washington, DC October 1989), pp 1-12

BOX 3-2: Cost-Benefit Analysis at FAA (Cont'd.)

Timing of Benefits

Benefits realized before the current date are categorized as "actual, " "Accruing" benefits occur over the CIP planning horizon—to be realized as a result of projects that have been Implemented before the current date—and are considered future benefits. Only future benefits figure into a project's cost-benefit ratio.

Several changes have been made in the methodology used to calculate the CIP benefits since analyses were first done for the National Airspace System Plan in 1981 Prior to 1986, benefits to aviation system users were not part of the analysis, The planning horizon for counting benefits was expanded from the year 2000 to include a project's entire life cycle, a timeframe from 1991 to 2025,

FAA's economic analysis of the 1991 CIP yielded a present value of $55.1 billion in future benefits,[6] $16,2 billion in future costs, and a benefit to cost ratio of 347 (See table 1 for relative shares of the benefits by category for both FAA and aviation system users.) However, if delays are not as bad as predicted and benefits to passengers are only 20 percent of the total benefits, for example, this cost-benefit ratio could be less than 1.

An alternate method of describing the benefits realized by users is to break them down by how they are calculated: 57 percent of total CIP benefits are passenger time savings and 24 percent are due to aircraft direct operating cost savings The six CIP projects that make the largest contribution to total benefits are listed in table 2.

TABLE 1: FAA Estimates of Future Capital Investment Plan Benefits

Category	Percent of future benefits[a]
FAA	
Air traffic controller productivity gains	5 3%
Maintenance personnel savings	2 7
Nonlabor-related operational savings	4 4
Total for FAA	12.4
Users	
Reduced delays	607
Increased availability of more efficient routes	20.7
Avionics cost savings	2 6
Reduced risk of accidents	3.6
Total for users	*87.6*
Total	**100.0**

[a] In 1991 dollars, the estimated value of *undiscounted* future benefits between 1992 and 2025 is $2579 billion Total projected discounted benefits of FAA's 1991 Capital Investment Plan are $551 billion

SOURCE Office of Technology Assessment, based on 1992 Federal Aviation Administration data

TABLE 2: 1991 Capital Investment Plan Projects With Largest Estimated Future Benefits

	Percentage of total CIP benefits[a]	
Project name	**User**	**FAA**
Advanced Automation Program[b]	**32,2%**	*3.7%o*
Global Positioning System Monitors	18,8	0.5
Microwave Landing System	10.4	**0.2**
Central Weather Processor	7,1	**0 0**
Terminal ATC Automation	5.6	**0.0**
Traffic Management System	2,2	1.9
Total for top six projects	**76.3**	**6.4**

[a] In 1991 dollars, the estimated value of *undiscounted* future benefits between 1992 and 2025 is $2133 for the top six projects and $2579 billion total The total projected discounted benefits of FAA's 1991 Capital Investment Plan are $551 billion Totals may not add due to rounding

[b] Includes 10 separate projects For a description of these projects see U S Department of Transportation, Federal Aviation Administration, *Capita/ Investment Plan* (Washington, DC December 1990)

SOURCE Off Ice of Technology Assessment based on 1992 Federal Aviation Administration data

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[6] The values in this section are in 1991 dollars

[7] Federal Aviation Administration, "An Economic Analysis of the 1991 Capital Investment Plan " unpublished document, May 1992

delay and increased safety.[74] In 1991 dollars, the estimated benefits for a subset of the RE&D program are $31.3 billion.[75] Table 3-9 presents the relative shares of these benefits broken down by category and by how the benefit was quantified.

TABLE 3-9: Relative Shares of Projected Benefits for Selected FAA RE&D Plan Projects

Benefit grouping	Percent of benefits
By *benefit category*	
Improved system capacity and reduced delays	91 .4%
Cost savings, Improved efficiency of operations, and Improved safety and security	8.6
Total	**100.0**
By how benefit was quantified	
Passenger time savings	470
Reduced aircraft operating costs	43.8
Increased controller productivity and other savings	9.3
Total-	**100.0**

NOTE Projected benefits are the operational benefits for the systems and technologies that might be derived from the RE&D program, and are associated with the Implementation of a subset of the projects included in the 1991 RE&D plan Benefits are calculated for the period 1992 through 2105 Total projected discounted benefits (in 1991 dollars) for this subset of RE&D plan projects are $31 3 billion

SOURCE Volpe National Transportation Systems Center, 1992

Limitations to Cost-Benefit Analysis for R&D

FAA faces some obstacles in adapting CBA for analyzing its R&D priorities. For example, it is not entirely appropriate to attribute the benefits from a future operating system in the field to a particular RE&D program. Because the benefits of the program are realized far in the future (perhaps 15 to 30 years), it is difficult to predict whether the RE&D program will result in new systems that can be implemented as part of the National Airspace System. The nature of R&D is such that only a fraction of the research undertaken results in the development of beneficial technologies. Those new technologies will only yield benefits if they can be successfully integrated and operated within the NAS. Recently, FAA has taken steps to define clearly the linkage between RE&D initiatives and broader agency objectives .76 Also, with assistance from the federal Center for Advanced Aviation System Development, FAA's Research and Development Service is attempting to develop ways to measure achievement of its R&D goals.[77]

Another limitation of R&D cost-benefit analysis is that data are often not sufficiently robust to allow reliable calculations of potential benefits. Projected benefits occur in the distant future and depend on a multiple-step process: successful research resulting in new technologies; fielding of new technologies; and, finally, benefits being realized from operation of the new system. In the case of capacity-related projects, delay forecasts are problematic—lending uncertainty to the baseline costs and projected net benefits to be derived from airspace capacity and efficiency enhancements. Better delay data and improved models of airspace and air traffic could reduce some of the uncertainty (see Delay and Air Traffic Analysis section below).

A third difficulty is reliably calculating the costs of conducting RE&D projects and implementing the resulting technologies. In particular, given the uncertainty of projecting 15 to 30 years into the future the costs of implementing and operating systems that do not currently exist, estimates of these costs would be subject to error.[78]

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[74] Volpe National Transportation Systems Center, "Benefits Evaluation of the FAA's Research, Engineering & Development Program," project memorandum, Jan. 14, 1992.

[75] Ibid.

[76] See Federal Aviation Administration, op. cit., footnote 42, pp. 1-7—1-13.

[77] Tony Dundzila and Sam Bowden, The Mitre Corp., Center for Advanced Aviation System Development, "Baseline Measures for Goals in the R.E&D Plan," draft working paper, November 1993.

[78] VNTSC, in its 1992 assessment, did not include the costs of individual programs needed to yield benefits.

According to FAA, the purpose of CBA is to allow the comparison of net benefits from disparate sorts of projects.[79] OTA finds, however, that CBA has not matured (o the point that it is effective for comparing R&D projects in different missions. When probable risk cannot be determined, as in security, the difficulties in estimating benefits and costs of R&D programs are compounded. This undermines direct comparison of investment benefits, e.g., between security and capacity or safety projects. Furthermore, within a program area, while a dollar value can be assigned to minimizing safety hazards or economic penalt ies (e.g., those asso-ciated with glycol disposal or recycling costs), not all benefits of improvements sought through R&D can be quantified. Examples include the value of "peace and quiet" and fewer emissions.

It is also doubtful that CBA can be effective in gauging the value of risk assessment efforts or more basic research, for example, long-term weather research. Improved understanding of weather phenomena through mesoscale meteorology research is integral to: defining usable airspace through understanding the behavior of thunderstorms and related hazardous weather phenomena: identifying regions of clear air turbulence and icing; predicting short-term changes in ceiling and visibility at airports; and understanding the meteorological elements that sustain wake vortex turbulence.[80] Yet FAA's RE&D budget contains no funding for this type of research,[81] and its weather R&D effort is focused primarily on new tools for processing and displaying increasing amounts of weather information generated by a modernized weather service.[82]

Neither the magnitude of a problem nor potential savings can be the sole determinant of the level of support required to devise solutions for any of the mission areas. In some cases, the technology base (including personnel and facilities) already exists upon which new or enhanced options can be constructed (e.g., cockpit weather displays). Other questions or difficulties (e.g., atmospheric science for environmental protection or weather forecasting) require more extensive effort before sufficient data can be gathered and assessed and options presented. Assessing the myriad human performance issues requires that measurement methods be developed and validated.

A broad portfolio of aviation R&D is therefore necessary, with research and technology needs derived from user input, analysis of performance trends, expert review, and breakthroughs in related areas of study. Many R&D investment planning decisions must still transcend the CBA methodology described above. For example, a more appropriate quantitative method for setting capacity-related research priorities may be a "needs" analysis that allows decisionmakers to focus on the operational systems required for the NAS in the future rather than the potential operational benefits that will result from the successful development of projects currently in the RE&D plan.

PREDICTING FUTURE PROBLEMS

The phrase "tombstone technology" is used. often disparagingly, to describe safety measures developed after an accident or series of accidents has occurred. But pursuing a focused development program before an accident occurs is risky and may divert precious funds from areas where prob-

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[79] Carlton R. Wine Manager In formation Systems, FAA Office of Aviation Policy, Plans, and Management Analysis, personal communication, June 17, 1994.

[80] Arthur A. Shrantz, Associate Director, Research Applications Program, National Center for' Atmospheric Research, personal communication, Apr. 6, 1994.

[81] Of FAA's $250 million fiscal year 1994 request for RE&D funding, $1.9 million is included for weather R&D; all of this is devoted to the integrated airborne windshear research program, a primarily technology-oriented effort.

[82] See discussion of FAA's Aviation Weather Development program in ch. 4.

lems may crop up sooner. For example, even if FAA or other agencies had supported more extensive materials science R&D in the late 1970s or early 1980s, it is not known whether the aging aircraft problem could have been averted before the Aloha accident occurred, nor is it clear that the expenditures in time and money (and opportunity costs) would have been fitting in light of the few fatalities to date.

In addition to aging aircraft and terrorist threats, other risks arise from an evolving industry, including highly complex software, the susceptibility of new avionics and digital systems to electromagnetic fields, increased use of composite materials, changes in aviation fuels and engine designs, and replacement of halons in fire extinguishing systems.[83] Other new issues relate to demographics, aviation's role in global climate change, and operation of the proposed very large commercial transports.

Based on FAA estimates that approximately 80 percent of its safety R&D has near-term applications, OTA calculates that less than 5 percent of the safety effort is longer term, generic knowledge gathering.[84] However, one future catastrophic accident that arises from anew mode of failure could cause as much damage and loss of life as many of the problems known to date. Predicting potential catastrophic problems requires a combination of improved data collection and analysis and generic research in order to confidently identify performance trends and derive a basic understanding of the elements (e.g., materials behavior and cognitive skills) that could contribute to such an accident.

Rather than focusing nearly all resources on specific problems, greater emphasis on operations research or analysis and risk assessment may be appropriate. The object of this activity is to examine elements of the aviation system for sensitivity to changes in technology or procedures, for example, the impact of deregulation and resultant shift to hub-and-spoke operations on capacity and safety.

Furthermore, this capability could be useful in better defining, prior to establishing requirements, the objectives of any technology development program. Key parts of this approach are integrated databases and assessment tools to support timely analysis of the state of the airspace system, and validated, appropriately scaled models for estimating traffic, environmental impact, and weather.

Additional cooperation with other federal agencies to leverage R&D dollars could be helpful. For example, the Department of Defense (DOD) national laboratories have an extensive background in aviation R&D and much of their work applies to FAA missions.[85] In 1993, in response to congressional direction, FAA performed a survey of external laboratory capabilities and identified 128 facilities whose work could benefit FAA; working agreements had already been established with 36 of these, but FAA found the capabilities of some of the remaining labs were too narrow in scope or had less than substantial relevance.[86] FAA plans to conduct further assessments of the advantages of fuller participation with certain DOD laboratories.

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[83] U.S. Department of Transportation, Federal Aviation Administration, *1993 Federal Aviation Administration Plan for Research, Engineering and Development*, Report of the Federal Aviation Administration to the U.S. Congress pursuant to Section 4 of the Aviation Safety Research Act, Public Law 100-591 (Washington, DC: February 1994), p. 6-1.

[84] The remainder is directed at long-term technology development programs.

[85] Gellman Research Associates, "Cooperation and Coordination in Federal Aviation Research," OTA contractor report, Dec. 30, 1992, p. 39.

[86] U.S. Department of Transportation, Fe&-a] Aviation Administration, *Survey of Research, Engineering, and Development Research Facilities*, Report of the Federal Aviation Administration pursuant to House Report 102-639 on the DOT Appropriations Act for FY 1993, Public Law 102-388 (Washington, DC: July 1993), p. 4.

Congress, in the 1990 Catastrophic Failure Prevention Act, also enabled FAA to provide grants to universities for exploring long-term R&D questions. In May 1992, the first recipient was selected; by July 1993, 58 grants totaling in excess of $32 million had been awarded.[87] Research areas include ATC automation. artificial intelligence, human factors. simulation, airport planning and design, aviation security, and aviation safety.[88]

FEDERAL AVIATION DATA AND ASSESSMENT RESOURCES

There are a variety of federal resources and efforts to gather information for determining the state of the aviation system (e.g., number of delays, operations, passengers), assessing or predicting potential problems (e.g., accident risk or security threat, environmental impact, capacity shortfall), and identifying technology and operational improvements to the system. In addition, performance data and analyses arc useful for developing R&D program goals and gauging the progress of those problem-solving efforts. While the current data-gathering effort sheds light on the issues confronting the industry, some key information is lacking.

This section describes the primary resources for each of the key mission areas and identifies further data and assessment tools needed to improve both the understanding of operational issues and R&D decisionmaking.

I Capacity-Related Data and Analysis

Information needs for airspace capacity assessment and air traffic management include:

- sources and characteristic lengths of delays, in order to support operational decisions and forecasts of activity and delay:
- improved short-term predictions of weather, which are essential to more efficient use of airspace as well as flight safety; and
- performance characteristics and longevity of critical infrastructure, for example, runways and other airport surfaces.

Delay and Air Traffic Data

The two primary delay reporting systems in use today are maintained by DOT and by FAA's Office of Air Traffic System Management.

DOT's Airline Service Quality Performance (ASQP) system stores data submitted by major airlines with service at the nation's top 100 airports. Actual departure time, flight duration, and arrival time are recorded and compared with the equivalent data published in the *Official Airline Guide* and listed in the computerized reservation system. Under the NAS Analysis Program, FAA collects data from 55 major airports and all 20 air route traffic control centers within the continental United States to track the number and length of delays (of 15 minutes or more) at airports or within ATC sectors. Each night, controllers relay delay information noted on flight strips[89] via the Operational Performance System Network (OPSNET) computer to FAA headquarters, where the data are compiled for the next day's status briefings. OPSNET also supports the compilation of statistics for a biennial report to Congress on NAS performance.[90]

OPSNET and related databases have some drawbacks. Chief among them are that the quality and completeness of controller reports vary with

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[87] Ibid., p. 4.

[88] Gellman Research Associates, op. cit., footnote 85, p. 11

[89] Marked with flight data, these paper strips serve as memory aids for controllers and as the backup system for automated surveillance and traffic display systems.

[90] Pat Beam, Manager, NAS Analysis Program, Federal Aviation Administration, personal communication, Aug. 6, 1993.

workload; and only delays of a minimum magnitude are reported, distorting the estimate of average and overall delay.[91] Unlike ASQP, OPSNET does not reflect airline-related delays, because the system records delay from the point an aircraft enters the takeoff queue. ASQP, OPSNET, and other sources of airline delay data are outlined in **box 3-3.**

Models and Analytical Tools

Today, capacity analysis uses a full spectrum of models in three key areas—policy analysis, detailed design, and operations support—to assess activities on different scales in order to determine where the bottlenecks are and under what conditions. The object is to revise operations and procedures as needed and to predict air traffic manage-

BOX 3-3: Sources for Airline Delay Data

ACARS	*Aeronautica/Radio, Inc. (ARINC) Communications and Reporting System* provides data (i.e., when the cabin is pressurized and the aircraft leaves the gate, wheels fold into wells, wheels lowered, and aircraft stopped at arrival gate and cabin depressurized) to track flights for the approximately 3,500 ACARS-equipped aircraft
ARTS	*Automated Radar Terminal System* provides runway use data, instrument flight rules (IFR) and visual flight rules airport operations data, and airline, flight number, and aircraft Information,
ASQP	*Airline Service Quality Performance* provides comparison of actual versus scheduled flight times for airlines with 1 percent or more of enplanements
ATA	*Air Transport Association* provides a monthly report to the Federal Aviation Administration on delays by phase of flight, derived from ACARS messages,
CATER	*Collection & Analysis of Terminal Records (managed by Aviation Data Systems) gives* flight strip and airport configuration data, along with winds/ceiling data for the few airports served by CATER, Does not provide flight plan data
CODAS	*Consolidated Operations and Delay Analysis System* uses ETMS (see below) data (indicating when centers takeup and give away flights to approximate takeoff and touchdown times) to supplement ASQP Information, the goal is monthly reporting of statistical delay data, Does not reflect causes of delay.
ETMS	*Enhanced Traffic Management System* utilizes host computers for providing flight plan versus actual flight data, but does not reflect ground Information. Includes only IFR flights.
OPSNET	*Operational Performance System Network* includes delays of 15 minutes or more *in* departure and arrival queues and en route. Includes general aviation, air taxi, and military flights, but cause of delay identified only when workload permits, (OPSNET is a subsystem of FAA's Air Traffic Operations Management System—ATOMS)

SOURCE Federal Aviation Administration, Office of Aviation Policy, Plans, and Management Analysis, 1993

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[91] These problems go back to the early 1980s. In addition, all databases measure delay against the *Official Airline Guide* times, which may have resulted in overestimates and underestimates of delay at different airports due to differences in typical taxing and queuing times and the inflation of schedules to improve on-time performance. See U.S. Congress, Office of Technology Assessment, *Airport System Development*, OTA-STI-231 (Washington, DC: U.S. Government Printing Office, 1984), p. 50.

ment and infrastructure environments of the future.[92]

Operational models

FAA's Air Traffic Control Systems Command Center, responsible for daily traffic control planning, uses both real-time. interactive analyses and offline analyses after the fact (see table 3-10). To enable controllers in centers to similarly respond to changing traffic conditions, computer-based decision aids with electronic databases are being developed.

Design models

Analyses of ATC system configuration and the environmental impact of changes to the system rely on detailed models of air traffic, which also support airspace and airport design. SIMMOD[93] is the best known of these and is used to simulate how airplanes interact in different regions, including detailed airport operations.[94] The Sector Design analysis tool, in trial use at three sites, is intended to allow ATC to redesign sectors to increase capacity and balance workload. FAA also is using the Graphical Airspace Design Environment (GRADE) computer graphics tool. Incorporating radar data, airspace geometries, and geographical information, GRADE analyzes and displays the effects of airspace modifications and changes in flight procedures.[95] FAA is seeking to adapt this visualization tool, with the support of its vendor, to permit concurrent analysis of noise impacts.[96]

TABLE 3-10: FAA Models for Traffic Flow Management and Capacity Analysis

Model	Purpose	Description
NASSIM	**Strategy evaluation**	'**Detailed** National Airspace System-wide traffic prediction and simulation
FLOWSIM	Strategy evaluation	Daily flow simulation for fast-time national major airport traffic.
SMARTFLO	Strategy generation	Planning for quick-response flow advisories using expert systems,
OPTIFLOW	Strategy generation	Optimized flow planning for dynamic national traffic flow simulation.
Planned arrival and departure system (PADS)	Strategy generation	Real-time development of optimal arrival and departure scheduling plans
High-altitude route system (HARS)	Strategy generation	Enables optimized, fuel-efficient jet routes
Daily decision analysis system (DDAS)	Information and analysis support	Automation tools to allow quick analysis of airline schedule change Impacts.

SOURCE Office of Technology Assessment, 1994, based on the 1993 FAA Research, Engineering and Development Plan.

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[92] Policy analysis models tire characterized by their approximate, macroscopic nature; detailed design or planning models are highly accurate and use simulations extensively; operations support models tend to be very fast, accurate, and microscopic, but those used for offline, post analyses need not be real-time. See Amadeo Odani, Massachusetts Institute of Technology, *Transportation Modeling Needs: Airports and Airspace* (Cambridge, MA: U. S, Department of Transportation, Volpe National Transportation Systems Center, July 1991). p. 8; and Saul I. Gass, University of Maryland, "Evaluation of Air Traffic Modeling Tools: Validation and Review of Results and Documentation," paper prepared for the Federal Aviation Administration, Oct. 16, 1992, p. 91,

[93] A trademark name for an airport and airspace simulation model.

[94] SIMMOD is a stochastic model; multiple simulation runs must be performed to lend results any statistical significance. The model now can be directed to perform iterations until a specified confidence level is achieved.

[95] Federal Aviation Administration, op. cit., footnote 50, p. 5-19.

[96] GRADE is a privately owned, proprietary tool. As of August 1994, contract negotiations are under way to merge the tool with FAA's Integrated Noise Model (see section on environmental assessment); the combined function is expected by the end of fiscal year 1995. FAA also hopes to further Integrate several of its capacity models into the revised tool. which could serve as the parent program for rapid analysis and visualization of interrelated changes in traffic, noise impact, and airspace design. "In this case, a picture's worth a billion worals." Richard Nell, Manager, Airspace Design Division, FAA Office of System Capacity and Requirements, personal communication, Aug. 4, 1994.

FAA's National Airspace System Performance Analysis Capability (NASPAC), which is ". . . essentially the first effort to develop a system-wide model of airport and ATC activities,"[97] has had several applications.[98] A second network model used to evaluate the national system is AIRNET. Intended for policy analysis, AIRNET has the advantage of being much faster, but does not have the same level of detail and does not reflect changes in airspace configuration.[99]

Model limitations and data requirements

A basic requirement for all models is that they correctly interact.[100] For example, the results of analyzing a problem situation using a network model must be consistent with results from a regional or airport model. However, the data reporting shortcomings limit FAA's ability to accurately model the airspace/airport operations. For example, the various data gathering systems have used different definitions of delay.[101] **An unambiguous definition of delay, in the context of flight routes and airport configurations, accepted by both airlines and FAA is needed.** Comprehensive analysis of the potential benefits of technology and procedure changes to the airspace system hinges on this capability. Furthermore, the National Simulation Capability[102] under development requires a baseline against which future performance of the National Airspace System can be evaluated.

Three divisions within FAA are exploring ways to consolidate data systems and enhance analytical capabilities. The Office of Operations Research (A OR) is developing CONDAT, a central memory bank for its suite of operational analysis tools (see table 3-10 again); CONDAT will permit AOR models to share data and analysis results.

In response to a congressional request for ATC performance assessment, FAA's Office of Air Traffic System Management conducted a study of NAS data for one day's activities to better understand issues affecting en route sector throughput. The initial study recommended an extended collection of operational data, including ground activity data from airlines, to support further analyses of NAS performance, trends, and throughput.[103]

FAA's Air Traffic System Management Office went on to establish a national flights database required for the broader assessment and a system for further automating and integrating delay information reports and improving ATC performance analysis. The project's objectives included a reusable product, one based on government and commercial off-the-shelf systems, and adaptability. With assistance from the Department of Energy's Oak Ridge National Laboratory, the Center for Naval Analysis, and Martin Marietta's Energy Systems, Inc., FAA developed the methodology to gather and integrate data from airlines and FAA's ATC facilities in order to represent an air-

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[97] Odani, op. cit., footnote 92, p. 63.

[98] Although undergoing further development. NASPAC has been used for several years at the Center for Advanced Aviation System Development and the FAA Technical Center, and was used to assess the nationwide and local impacts of the proposed Denver International Airport. It has been adapted for analysis of European airspace issues. Fearnsides, op. cit., footnote 22.

[99] Alan Breitler and Carl ton Wine, FAA Office of Policy, Plans and Management Analysis, Planning Analysis Division, personal communication, Jan. 26, 1993.

[100] Gass, Op. cit., footnote 92. p. 118.

[101] Odani, Op. cit., footnote 92, p. 75.

[102] The National Simulation Capability is comprised of: a simulation system at FAA's Technical Center; several laboratories engaged in National Airspace System R&D; and the Integration and Interaction Laboratory, a proof-of-concept demonstrator developed by the Mitre Corporation. The system is intended to integrate various RE&D program elements across the NAS environment, permitting early requirements validation, problem identification, solutions development, and system capability demonstration. U.S. Department of Transportation, Federal Aviation Administration, *Airport Technology Program Plan* (Atlantic City, NJ: Federal Aviation Administration Technical Center, November 1991), p. 2-66.

[103] *Lee* Berry et al., Oak *Ridge* National Laboratory, *An Analysis of the National Airspace Capacity*, report prepared for the Federal Aviation Administration. Office of Air Traffic Management, K/DSRD-1098 (Oak Ridge, TN: Martin Marietta Energy Systems, Inc., Sept. 29, 1992). p. 7.

craft flight from gate to gate and calculate delays within any flight leg.[104] As yet, however, it cannot develop "what if' scenarios on a national scale.

The Office of Aviation Policy, Plans, and Management Analysis is developing the Consolidated Operations and Delay Analysis System (CODAS), which combines host computers, ASQP, and the National Oceanographic and Atmospheric Administration (NOAA) weather information (when available) and calculates delay by phase of flight for instrument flight rules operations from all airports. The intended product is a reliable statistical database from which definitions for delays can be standardized (e.g., average delay between city pairs for specific airports/runway configurations).[105] According to FAA, the flights represented by CODAS account for roughly 95 percent of system delays.[106]

Rather than daily assessments of traffic conditions (e.g., for central flow control), CODAS will support non-real-time analyses and projections of delays in future scenarios. Retrieval of key information for CODAS, i.e., runway configuration data, has yet to be finalized; a "patch" on Automated Radar Terminal System computers is the likely mechanism for automated collection of this data.[107] In addition, there is a rule in progress for airlines to report, via the ARINC Communications and Reporting System, the exact times on takeoff and touchdown.

Weather Data

In the past, an insufficiently dense weather observation network made it impossible to resolve weather phenomena on space and time scales necessary for aviation operations.[108] Next-generation weather radar (NEXRAD) and the Automated Surface Observing System (ASOS) are two elements of a broad weather service modernization program being conducted jointly by FAA, NOAA, and DOD to meet this data need. NEXRAD utilizes Doppler radar technology to provide improved estimates of precipitation amounts, detect the transition between rain and snow, track storm movement and intensity, and allow for earlier detection of the precursors of thunderstorm development and other important weather phenomena. ASOS provides the basic ground-level data required for severe weather forecasting and for support of aviation operations.[109]

Satellite-based observation platforms (e.g., the Geostationary Operational Environmental Satellite) provide images of clouds and precise atmospheric soundings, additional data that are required for accurate and timely warnings of severe weather. By 1995, daily weather observations using these and other measurement systems are expected to increase 30-fold relative to 1985 levels, significantly enhancing the understanding of the state of the atmosphere.[110] The ability to process these data and present results in useful formats to the aviation community rests on advances in computing, communications, and display technologies (see chapter 4).

Runway Pavement Performance Data

Pavement requires regular maintenance in order to seal cracks and repair damage, and major rehabilitation is usually required every 15 to 20 years to correct the effects of age and exposure. Pavement

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[104] The system reflects activity over the entire NAS for selected periods in late 1991 and early 1992.

[105] Alan Brietler, FAA Office of Aviation Policy, Plans, and Management Analysis, presentation to the Transportation Research Board, Jan. 12, 1994.

[106] Brietler and Wine, op. cit., footnote 99.

[107] Ibid.

[108] U S Department of Transportation, Federal Aviation Administration, A *Weather Vision To Support Improved Capacity, Efficiency, and Safety of the Air Space System in the Twenty-first Century* (Washington, DC: April 1992), p. 4.

[109] National Research Council, Commission on Engineering and Technical Systems, Committee on National Weather Service Modernization, *Toward a New National Weather Service*, Second Report (Washington, DC: National Academy Press, March 1992), p. 33.

[110] Federal Aviation Administration, op. cit., footnote 108, p. 4.

FEDERAL AVIATION ADMINISTRATION

Gradual wear and loss of serviceability are the most common airport pavement issues, although catastrophic pavement failure can occur

wear is a factor of aircraft axle weight distribution (determined by the type and weight of aircraft), moisture (usually from rainfall or melting snow), temperature, fuel spillage, and construction and maintenance,[111] Neglected pavement can lead to foreign objects on the airport surface, which can damage propellers, turbines, and landing gear.

The advent of new landing gear and tire configurations, faster landing speeds (e.g., those associated with the proposed HSCT), and potential ultra-high-capacity aircraft with weights exceeding 1.3 million pounds require that new design methodology for runway pavements be developed. [112] FAA is planning a long-term data collection effort for assessing pavement performance. The National Airport Pavement Registration and Demonstration Program will use sensors imbedded in the new Denver International Airport runways to provide data for validating pavement design theory. Modeled after the Strategic Highway Research Program, it will annually identify new airport construction to determine pavement life-cycle costs and other performance factors. [113]

Safety Factors

Fatality and accident rates are the primary measure of safety. Safety factors are derived from events or procedures related to passenger fatalities.114 NTSB maintains the largest collection of accident data and, with assistance from FAA and aircraft manufacturers, determines probable cause. Boeing and McDonnell Douglas also have extensive accident databases and analytic staffs.

In addition to accident-incident data and causal factors, there are secondary and tertiary factors with which changes in safety can be measured or forecasted. These include airline operating, maintenance, and personnel practices and federal ATC management practices. Also, regulatory and corporate policies influence these practices.

While studies of aggregate accident data are useful in identifying and understanding existing

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[111] The spread of the weight over the gears and tires is more important than total weight; e.g., a 727 can cause more pavement wear than a heavier aircraft that distributes its weight over a greater number of tires.

[112] Current airport pavement design methods evolved from highway design theory developed in the 1920s and applied to aviation in the 1940s and 1950s, Further design standards were established between 1968 and 1970 through research on two- and four-wheel landing gear, as used on narrow-body aircraft (200,000 to 400,000 pounds). The design theory was successfully extended for 747s, but the pavement loading characteristics of newer heavy aircraft, such as the B-777 and the proposed MD-12, are not well understood, nor have they been tested.

[113] Federal Aviation Administration, op. cit., footnote 83, p. 5-4.

[114] See U.S Congress, Office of Technology Assessment, *Safe Skies for Tomorrow: Aviation Safety in a Competitive Environment,* OTA-SET-381 (Washington, DC: U.S. Government Printing Office, July 1988), p. 69.

problems, the infrequency and variability of major accidents limit FAA's ability to measure aviation safety and estimate short-term changes in risk. Supplementing the accident data is a host of federal safety data resources, including operational databases managed by the FAA Associate Administrators for Aviation Standards, Air Traffic, Regulation and Certification, and Aviation Safety; and specialized data systems kept by NTSB, DOT's Research and Special Programs Administration, and DOD's Air Mobility Command.[115]

Key difficulties in using federal aviation databases identified in the past include consistency and availability y of data, accessibility and compatibility of various data systems, and an emphasis on administrative purposes in the design and use of databases that makes analysis difficult.[116] These issues and problems with inaccurate, incomplete safety and inspection data have prompted FAA to improve its data collection and assessment capabilities.

Safety Data and Indicators

In 1988, FAA established the Safety Indicators program to improve its forward-looking ability to measure and manage aviation safety. Program objectives included both developing and monitoring key safety indicators, and developing a computer analysis tool. The latter, designated an automated decision support system, was intended to obtain information from existing safety databases for sophisticated analysis and presentational But, FAA's progress was limited: according to GAO, the lack of effective user involvement and unclear management commitment helped to delay development of five categories of safety indicators and the analysis tool.[118]

In 1992, the Associate Administrator for Aviation Safety (ASF) established a high-level task force to reexamine the indicators effort.[119] After soliciting input from technical staff that use the various FAA databases. ASF revised the program to reflect trends in accidents and incidents, measures of efficiency and compliance with FAA regulations, and inspector activity.[120] In addition, the new Systems Indicators program includes data on the general operating environment to illustrate potential demands on the aviation system (e.g., gross domestic product, enplanement forecasts, and numbers of certificated airports and airmen).[121] FAA has produced quarterly reports on systems indicators since 1993 for in-house consumption; an annual report to an external audience is in the works.[122]

In recent years. FAA also has begun to integrate its safety databases. The first to be integrated were

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[115] Another important source of safety data is the Aviation Safety Reporting System (ASRS), administered by NASA, funded mainly by FAA. and maintained with NASA guidance by the Battelle Memorial Institute. Pilots. controllers, and others submit voluntary and confidential accounts of safety-related incidents to the system. This and other safety databases are described in more detail in OTA's 1988 report, *Safe Skies for Tomorrow. See* ibid., p. 85.

[116] Ibid., p. 77,

[117] U.S. Congress General Accounting Office, *Aviation Safety: Progress on FAA Safety Indicators Program Slow and Challenges Remain*, GAO IMTEC-92-57 (Washington, DC: August 1992), pp. 2-3.

[118] The categories are air traffic, flight operations, aircraft certification, airports, and security. Ibid., p. 6.

[119] Steve Cohen, Safety Information and indicators Division, Office of the Associate Administrator for Aviation Safety, personal communication, May 6. 1994. See U.S. Department of Transportation, Federal Aviation Administration. "FAA System indicators Program Report," July 15, 1992.

[120] Cohen, op. cit., footnote 119.

[121] Associate Administrator for Aviation Safety, Office of Safety Information and Promotion, *Aviation System Indicators*, vol. 2, No. 1 (Washington, DC: Federal Aviation Administration, February 1994), p. 3-1.

[122] Cohen, op. cit., footnote 119.

incident databases directly managed by ASF.[123] Currently, **ASF** has ready access to NTSB accident databases and FAA's Accident Investigation Data System, along with earlier systems. As a result, FAA can quickly gather information from a variety of sources on a particular category of operations and prepare material for analysis by users inside or outside FAA.[124] Additionally, FAA is working toward integration of some administrative safety databases.

Inspection and Maintenance Data

Also useful for pointing out potential safety problems are data gathered by FAA's airworthiness and operations inspectors, and provided by the airlines and aircraft manufacturers. FAA's Flight Standards Service, under the Associate Administrator for Regulation and Certification, has attempted to improve the collection of these data and target personnel more effectively.[125] These efforts have had mixed success. A familiar contributing factor to the difficulties in upgrading the databases is FAA's failure to fully flesh out the requirements for the new databases and tools in advance of their development (see Problems in System Development and Acquisition in chapter 2).

According to GAO, inadequate oversight by regional and district office managers of safety inspection policies and omissions and errors in the entry of inspection data contributed to shortcomings in a previous automated program for tracking air carrier inspections, the Work Program Management Subsystem (WPMS).[126] The incomplete nature of the required inspections and reporting affected the data's consistency and limited the program's utility in safety analysis. In fiscal year 1990, FAA replaced the WPMS with the Program Tracking and Reporting Subsystem.[127]

In March 1990, FAA announced the launch of two new initiatives intended to improve air safety, the self-audit program and the voluntary disclosure program.[128] As they were originally designed, FAA could use data from both programs to target inspections and make for efficient use of inspector time. According to GAO, FAA did not clearly articulate basic implementation issues, provide convincing arguments on the merits of the programs, or adequately train its inspectors in the programs' benefits and execution; the result has been limited airline participation in the programs.[129]

In 1991, GAO found that the Service Difficulty Reporting System database, intended to allow

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[123] These four are Operational Error, Pilot Deviation, Vehicle, and Pedestrian, from which the Runway Incursion database is compiled. Charles Huettner, Deputy Associate Administrator for Aviation Safety, Federal Aviation Administration, personal communication, July 22, 1993.

[124] Robert Matthews, Special Assistant to FAA Associate Administrator for Aviation Safety, personal communication, May 10, 1994.

[125] According to GAO, there has been a shortage of fully trained inspectors for assessing compliance with both Operations and airworthiness requirements. U.S. Congress, General Accounting Office, *Aviation Training: FAA Aviation Safety Inspectors Are Not Receiving Needed Training*, GAO/RCED-89-168 (Washington, DC: U.S. Government Printing Office, September 1989), pp. I -2.

[126] U.S. Congress, General Accounting Office, *Aviation Safety: Inspection Management System Lucks Adequate Oversight*, GAO/RCED-90-36 (Washington, DC: U.S. Government Printing Office, November 1989), pp. 4-6.

[127] John Lapine, FAA Aircraft Safety program, personal communication, Apr. 19, 1994.

[128] Under the self-audit program, airlines are to: develop clearly defined safety evaluation organizations and ensure their independence; report evaluation results directly to the president or other top managers to ensure their involvement in resolving safety problems; conduct continuing, indepth analyses of such problems; and develop written audit schedules, corrective action plans, and complete records. The voluntary disclosure program was drafted to encourage airlines to report safety violations by extending amnesty for any fines or penalties if the airlines take corrective actions approved by FAA. U.S. Congress, General Accounting Office, *Aviation Safety: Progress Limited With Self-Audit and Safety Violation Reporting Programs*, GAO/RCED-92-85 (Washington, DC: U.S. Government Printing Office, March 1992), p. 3.

[129] Ibid., pp. 2-3, 8.

identification of trends in serious aircraft malfunctions, was also plagued with inconsistent, incomplete, and outdated data.[130] Since then, FAA has enabled airlines to enter data directly into the system and accelerated dissemination of the data by providing FAA's Flight Standards Service district offices with direct access to the database. FAA staff also attribute some improvements to the additional field experience many airworthiness inspectors now have when hired.[131]

Other FAA initiatives have had more success at the outset. With funding from the aging aircraft program, the Flight Standards Service established a research effort in 1990 to assist in monitoring the performance of FAA certificate holders (e.g., air operators. air agencies, and aircraft types). Like the original safety indicator program described above, the Safety Performance Analysis System (SPAS) initiative includes the development of an analytical tool, complete with performance indicators and supporting data.[132] However, there are key differences. SPAS metrics are more specific and are intended to help direct the agency's inspector workforce toward areas determined from statistical analysis of a wide array of performance data.[133] In effect, SPAS is an analytic engine that sits atop the Flight Standards Service's databases and monitors financial, maintenance, and operational trends. Data are updated every 24 hours and, using algorithms developed for FAA by the Volpe National Transportation Systems Center, SPAS generates statistical indicators for analysis of anomalies within like groups of aircraft or operators.

Phase 1 of SPAS addresses large airlines and regional commuters, which correspond to roughly 90 percent of the flying public. By 1994, the first phase of SPAS has been established at 17 sites for test and evaluation; a production model is expected, on schedule and under budget, in January 1995. FAA staff attributed the success of the program to learning from prior mistakes in developing analytic tools; and, more importantly, relying on an expert panel to establish system requirements and developing the system with early and frequent input from the project's primary users, FAA inspectors.[134]

Security Data

For security, relying on past threats as indicators of problems allows FAA to attempt to prevent similar incidents, but leaves the agency one or two steps behind in identifying new concerns. In turn, this makes the task of devising effective methods of countering a threat more onerous. Thus, FAA needs a constant flow of intelligence data. To support the intelligence requirements of the aviation security program, the Aviation Security Improvement Act of 1990 created new high-level security positions within DOT and FAA.[135] Figure 3-11 shows the positions and duties of these personnel and their relationship to one another.

The second key area of data needs relates to how deterrence technologies perform. Once a security technology is in the field, operational problems may and do arise. FAA regularly sends staff to the field to evaluate FAA- or airport-installed

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[130] U.S. Congress, General Accounting Office, *Aviation Safety: Changes Needed in FAA's Service Difficulty Reporting Program*, GAO/RCED-91-24 (Washington, DC: U.S. Government Printing Office, March 1991).

[131] Harlan Hillers, FAA Office of Flight Standards, Regulatory Support Division, personal communication, May 6, 1994

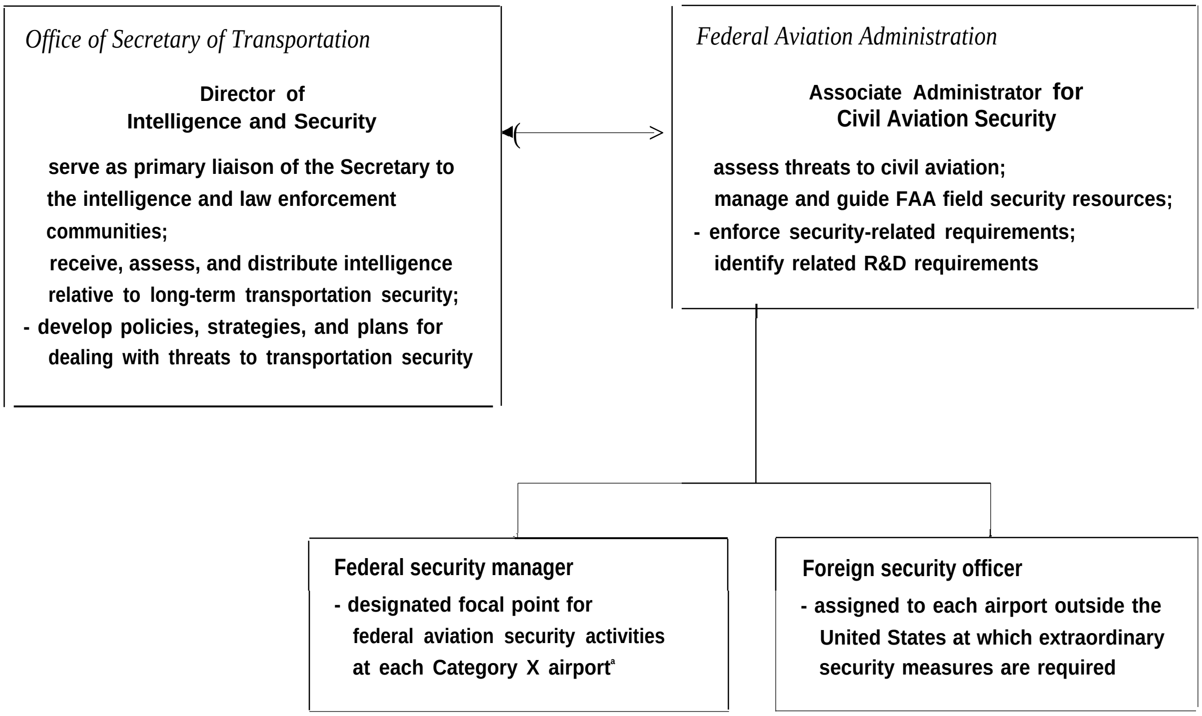
[132] Lapointe, op. cit., footnote 127.

[133] FAA inspectors, approximately 2,000 of them, are sent out to survey aircraft operations and maintenance activities. They log their observations and reports on the Performance Tracking and Recording System. Other data of interest are drawn from service difficulty reports, incident reports, and DOT financial information. Because only the largest carriers are represented in the latter data, FAA is looking to glean financial data on the other operators to support analysis of that risk factor, Frederick Leonelli, Manager, Aircraft Maintenance Division, FAA Flight Standards Service, personal communication, Apr. 29, 1994.

[134] Ibid.

[135] Public Law 101-604, Nov. 18, 1990. See U.S. Department of Transportation, Federal Aviation Administration, *Aviation Security Research and Development Plan* (Atlantic City, NJ: Federal Aviation Administration Technical Center, March 1992). p. 5.

FIGURE 3-11: Aviation Security Positions Created by the Aviation Security Improvement Act of 1990



Office of Secretary of Transportation

Director of Intelligence and Security

- serve as primary liaison of the Secretary to the intelligence and law enforcement communities;
- receive, assess, and distribute intelligence relative to long-term transportation security;
- develop policies, strategies, and plans for dealing with threats to transportation security

Federal Aviation Administration

Associate Administrator for Civil Aviation Security

- assess threats to civil aviation;
- manage and guide FAA field security resources;
- enforce security-related requirements;
- identify related R&D requirements

Federal security manager

- designated focal point for federal aviation security activities at each Category X airport[a]

Foreign security officer

- assigned to each airport outside the United States at which extraordinary security measures are required

[a] Category x airports (19) typically have a large number of passenger enplanements per year, along with departing international flights

SOURCE Office of Technology Assessment, 1994, based on FAA Aviation Security Research and Development Plan, March 1992

equipment and procedures. According to GAO, however, the Civil Aviation Security Information System (CASIS) that FAA uses to record the results of its inspections has several drawbacks. For example, GAO found that CASIS does not include information on the severity of a deficiency or how it relates to airport security as a whole. Nor can CASIS be used to determine whether unsatisfactory conditions reflect individuals' carelessness or the existence of systemic problems.[136] A more robust analytical approach would assist in evaluating security system strengths to further shape R&D plans and implementation methodologies.

Environmental Assessment

As concern over environmental degradation has grown in the United States and elsewhere, aviation's role has come under increased scrutiny. Ground-level emissions from aircraft and airport sources contribute to local air pollution (e.g., ozone formation). Aircraft emissions at higher altitudes are circulated and dispersed over much larger areas; although not unimportant or insignif-

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[136] U.S. General Accounting Office, *Aviation Security: Additional Actions Needed To Meet Domestic and International Challenges*, GAO/RCED-94-38 (Washington, DC: U.S. Government Printing OftIce, January 1994), pp. 42-45.

icant, they do not directly affect the immediate area of the release. It is difficult to quantify these emissions and determine their effects.[137]

Federal responsibility for aviation environmental issues is divided between EPA and FAA. The burden of collecting data for assessing environmental impact of aircraft and airport operations typically falls onto FAA's shoulders. For example, EPA's listing of all transportation emission sources uses data from FAA aircraft engine emission inventories. The listing, however, reflects only ground-level operations; the levels of engine emissions at cruise altitudes remain unknown. Neither agency maintains databases of other impacts on the environment (e.g., local air pollution, airports' use of deicing materials and their effects on water quality, and other substances that affect air or water quality).

Aircraft Noise Assessment and Modeling

No real-time monitoring of noise effects takes place on a national scale. Instead, FAA uses models to estimate the impact of aircraft noise on communities. The two most commonly used are the Integrated Noise Model (INM) and the National Noise Impact Model (NANIM).[138]

The Transportation Research Board (TRB) has suggested that these models could be enhanced considerably by combining the sound level estimates with population distribution and land use information.[139] Further improvements include incorporating the effects of local topography and meteorology on sound propagation, and verifying whether or not the models are valid at distances from the airport where climb-to-cruise noise may be the dominant noise source.

The Community Noise sub-element of NASA's Advanced Subsonic Technology (AST) Noise Reduction program is incorporating population density into noise impact models.[140] For FAA, DOT's Volpe National Transportation Systems Center is evaluating whether topography effects on sound propagation should be considered for the agency's models. In December 1993, FAA released a new version of INM that addresses nonstandard atmospheric conditions for prediction of takeoff-related noise. A second enhancement, expected to be released in January 1995, will include basic topography and demographic data (from geographical information systems) to refine calculations of community noise exposures.[141]

VNTSC has also developed software additions to INM to support analysis of noise impact of operations in transitional airspace (i.e., up to 18,000 feet altitude). This would support analyses of proposed flight plan modifications like those made for the Expanded East Coast Plan.[142] In addition, impact modeling efforts will be expanded to integrate aircraft noise certification and airport planning requirements (Federal Aviation Regulations Parts 36 and 150), along with flight operations data to enable air transportation system noise impact prediction.

Noise metric

In 1992, the Federal Interagency Committee on Noise (FICON) reaffirmed the adequacy of the current noise metric, the average sound level des-

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[137] Bryson, op. cit., footnote 15.

[138] The INM enables FAA to predict the distribution of areas adjacent to an airport that experience noise exceeding the levels recommended by EPA for residential neighborhoods. The Air Force uses a similar model called NOISEMAP for assessment of the impact of military operations. NANIM estimates the total U.S. population exposure.

[139] Transportation Research Board, "Environmental Research Needs in Transportation," Transportation Research Circular Number 389, March 1992, p. 30.

[140] Terrence J. Hertz, Manager, Advanced Subsonic Technology, Office of Aeronautics, National Aeronautics and Space Administration, personal communication, Apr. 26, 1994.

[141] Thomas Connor, FAA Office of Environment and Energy, personal communications, Oct. 18, 1993 and July 26, 1994.

[142] In the late 1980s, FAA began implementation of its Expanded East Coast Plan in order to reduce air traffic delays at the New York City area airports. The changes to the distribution of traffic resulted in many complaints about aircraft-related noise.

ignated as DNL, as the principal means for describing long-term noise exposure for civil (and military) aircraft operations.[143] However, FICON also recommended that the federal government increase R&D on: the "masking" effects of various types of nonaircraft noise when compared with aircraft noise; and including ambient noise in the current assessment methodology.[144] Furthermore, the introduction of engines with higher bypass ratios has shifted the dominant frequency in aircraft noise—a new metric may be required to reflect corresponding changes in perceived noise impact.[145]

TRB also recommended evaluation of supplementary noise metrics, because the existing DNL metric may not be sufficient in other situations. Three areas in which community response (i.e., expression of annoyance) to aircraft noise exceeds that expected using the DNL metric are:

- near small and mid-sized airports where the average impact of single aircraft overflights within a given DNL contour is much greater than the corresponding impact near a large airport,
- at points distant from airports where new air traffic patterns have introduced recognizable aircraft noise into regions that rarely experienced such noise events previously, and
- near airports where there has been a discontinuous increase in air traffic or a dramatic change in air traffic patterns.[146]

Air Quality and Global Climate Change

Aviation can affect the atmosphere on both local and global scales. For example, aircraft and airport-related operations have an impact on the attainment of regional ozone standards, air toxics levels, and smog.[147] Estimating the total quantity of pollutants and their impact on local air quality requires knowledge of specific pollutant emissions and their behavior in the atmosphere. In addition, subsonic aircraft engine emissions are suspected to contribute to global climate change (e.g., through nitrogen oxide and water vapor emissions at high altitudes).

In the United States, EPA calculates average emission factors for various types of aircraft and, using FAA-supplied operations data (i.e., the number of takeoffs and landings), estimates nationwide aircraft emissions.[148] Data on key pollutant emissions from other transportation sources are gathered from a variety of federal, state, and regional sources, and assembled for inclusion in EPA's annual national emission estimates document.

In most areas, the data indicate that air transportation-related contributions are small or insignificant when compared with other sources. However, because the methodologies for estimating emissions and assessing their air quality impacts have changed over the last decade, comparison of trends for source categories is suspect.[149] Addi-

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[143] Federal Interagency Committee on Noise, *Federal Agency Review of Selected Airport Noise Analysis Issues* (Washington, DC: August 1992), p. 3-1.

[144] Ibid., p. 3-11,

[145] Higher frequency noise generated by ultra-high-bypass engine fan blades can cause more annoyance or discomfort.

[146] Transportation Research Board, op. cit., footnote 139, p. 29.

[147] Alfred W. Lindsey, Director, EPA office of Environmental Engineering and Technology Demonstration, persona] communication, Apr. 18, 1994. Related activities include transportation to and from the airport, fueling, maintenance, and other surface operations.

[148] Estimates do not reflect activities above 3,000 feet. U.S. Environmental Protection Agency, *National Air Pollutant Emission Trends, 1900-1992, EPA-454' R-93-032* (Washington, DC: October 1993), p. 5-4.

[149] See ibid., ch. 5.

tionally, EPA estimates of aircraft contributions to pollutant emissions may suffer from use of dated information. The agency‘s comprehensive catalog of emission indices, designated AP-42, includes aircraft data from 1980.[150] While new EPA guidance material[151] now reflects FAA’s existing data, the AP-42 information pertaining to aircraft predates almost all of FAA’s data and the promulgation of hydrocarbon standards in 1984.[152]

The capability of analyzing local impacts is improving. In 1993, FAA and the U.S. Air Force jointly issued an updated Emissions and Dispersion Modeling System to assess air quality around airports. FAA also established and released the Aircraft Engine Emissions Database for use in calculating the emissions impacts of specific aircraft/engine combinations.[153] Over the long term, FAA and EPA may need to address emissions of air toxics from aircraft in addition to the nontoxic pollutants already included in the databases.[54]

An understanding of aviation’s historical global air pollution impact is lacking, thus additional data gathering and atmospheric modeling efforts to support assessment of upper atmospheric issues are required. A major unknown is the emission factors of engines at cruise altitude.[155] In June 1992, in preparation for the third meeting of the ICAO Committee on Aviation Environmental Protection, an emissions inventory subgroup initiated a study of global pollution from aircraft emissions.


GERMAN AEROSPACE RESEARCH ESTABLISHMENT (DLR)

Condensation trails (contrails) left in well-traveled flight corridors over central Europe Contrails and related clouds may have an effect on the Earth's surface temperature and climate, under certain atmospheric conditions, they can persist for many hours

Because the sizable modeling effort in place for NASA’s supersonic research program did not address subsonic aircraft effects on the upper troposphere, in April 1993 NASA established a Atmospheric Effects of Aviation Project. In addition to the continuing Atmospheric Effects of Stratospheric Aircraft element of the High-Speed Research Program, the new effort includes a subsonic assessment focused on defining the issues related to quantifying the impact of current and fu-

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[150] U.S. Environmental Protection *Agency, Compilation of Air Pollutant Emission Factors, Volume II: Mobile Sources*, AP-42 (Ann Arbor, MI: 1985). Aircraft data from 1980.

[151] U.S. Environmental Protection Agency. “Procedures for Emission Inventory Preparation.” Emissions From Aircraft, Chapter 5: draft, Nov. 1, 1991.

[152] A planned revision of AP-42 is on hold. Krull, op. cit., footnote 14.

[153] National Aeronautics and Space Administration, *Aeronautics and Space Report of the President: Fiscal Year 1992 Activities* (Washington, DC: 1993), p. 45.

[154] Lindsey, op. cit., footnote 147.

[155] Jack Durham, Director, EPA Office of Environmental Processes and Effects Research, personal communication, Apr. 18, 1994.

ture subsonic fleet emissions in both the upper troposphere and stratosphere.[156]

CONCLUSIONS

Despite significant advances in safety, airspace and airport capacity, and environmental protection, U.S. air transportation system problems remain. There are few, if any, easy solutions to human error and hazardous weather, costly delays from congestion and poor weather, and public displeasure and concern over aviation environmental impacts. Furthermore, defining the problems themselves is often an arduous task.

Consequently, the data collection and analysis requirements for aviation are daunting; for example, not only must the causes of accidents or delays be determined, but also the efficacy of R&D programs established to mitigate them. While new tools and methods of assessment are being developed to aid in this process, quantitative measures of performance or success are still lacking in some areas. Another limitation is that many R&D projects depend on broader FAA or federal activities for success. For example, the goal of introducing satellite-based nonprecision approaches into most U.S. airports by 1996[157] is one that can be attained only with a cooperative effort by FAA's R&D, safety, ATC, and airport divisions, along with airline operators and avionics manufacturers. Estimating the time and expense required to complete such an effort is problematic, making it difficult to compare the anticipated benefits of this type of R&D program with others. However, FAA is making progress in this endeavor and in its efforts to improve related databases and models.

Perhaps an even more difficult task for the agency has been establishing a more forward-looking analysis capability. OTA finds that a greater emphasis on assessing emerging risks—likely to arise in areas where we lack fundamental knowledge—is still needed. New security risks are examples, along with human performance in an increasingly complex system. FAA has upgraded its databases and developed new analytical tools for illustrating trends and assessing multiple safety, security, and environmental factors. With careful attention to the input and results, FAA will be better prepared to identify emerging problems. In addition to ongoing analysis of system activities and trends, long-term research is essential to continued gains in safety and security and mitigating the environmental impacts of aviation.

As the agency with responsibility for regulating many facets of the industry and operating the extensive ATC system, FAA is constantly faced with many challenges—all of them seeming to demand immediate attention and concerted effort. However, FAA's resources, like those of the federal government as a whole, are limited. Not all problems can be addressed at the same time or to the degree desired by the public, other members of the aviation community, or the government itself. FAA and its partners in aviation R&D must learn where their resources can be applied most effectively and conduct data collection and analysis to support priority efforts.

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[156] National Aeronautics and Space Administration, Office of Aeronautics, "Atmospheric Effects of Aviation Project Flyer," March 1994, p. 7.

[157] Federal Aviation Administration, op. cit., footnote 42, p. 1-13.