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AVIATION SYSTEM CAPACITY IMPROVEMENTS THROUGH TECHNOLOGY

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SUMMARY

This report expands upon a study conducted by the Flight Transportation Laboratory of the Massachusetts Institute of Technology (MIT). The primary objective of the MIT study was to determine the impact of technology on capacity improvements in the U.S. air transportation system and, consequently, to assess the areas where NASA's expertise and technical contributions would be the most beneficial. The outlook of the study is considered both near- and long-term (5 to 25 years). This report reinforces and supplements the conclusions reached in the MIT study, and includes assessments of the state of technology in those areas found to be critical to relieving congestion in the air transportation system. Improvements in technology are identified that are likely to increase capacity and reduce delays if developed and implemented.

INTRODUCTION

In the U.S., passenger transportation has experienced dramatic changes over the past half century. As the nation was recovering from World War II, intercity travel was linked across the country by railroad networks or by buses to points not served by the rail system. During this same period, cross-country travel by automobile was a challenge and travel by air was considered luxurious. In more recent years, those same rail and bus modes of transportation represent a very small and diminishing fraction of the total means of transportation. They have been replaced by privately owned automobiles traveling over a congested interstate highway system and by an ever expanding private and commercial air transportation network.

From about 1970 through 1990, there has been a boom in air travel essentially world wide. This has resulted from a combination of events that include improved personal economic standards, development of larger and faster aircraft, increased number of large and small airports serving the nation, and airline deregulation that occurred in 1978. This single mode of transportation has been responsible for altering intercity travel and currently represents about one-fifth of all intercity passenger-miles or about twice that in 1970 (ref. 1).

As we move into the next century, the U.S. will be facing many challenges in its transportation system. Probably one of the greatest challenges will be that of the air transportation system (refs. 2 and 3). In 1988, the top 100 U.S. airports accounted for 90 percent of the 459 million airline passengers who enplaned nationally. In 1998, about 715 million passengers are forecast to enplane at these same airports or a 56 percent increase. For the same airports and time period, aircraft operations are forecast to increase from approximately 25 to 34 million; a growth in operations of 36 percent. Current forecasts indicate that delays in air travel will reach staggering proportions (ref. 4) . In 1988, twenty-one U.S. airports exceed 20,000 hours of annual airline flight delays. By 1988, the number of airports which could exceed this number of hours is forecast to reach 41 (ref. 4). These delays have been said to cost the airlines about $32 million directly per airport and airline passengers $4 to $6 billion overall (ref. 5). Thus, the principal challenges facing the Federal Aviation Administration (FAA), as America moves into the next century, have been defined in their 1990 Strategic Plan (ref. 3) as being: (a) aviation safety and security; (b) capacity and access; (c) environment; (d) human factors; (e) internationalization; and (f) management of the agency.

On the plus side of the capacity crisis is that there has been a bonanza of revenues generated over the past several years by the escalation of passenger and cargo trade at the nation's commercial airports, which exceed 500 in number. This economic impact is supported by a study commissioned by the Partnership for Improved Air Travel (PIAT) indicating that in 1989, the direct impact of combined airline and airport operations, aircraft manufacturing, and general aviation was $86.5 billion. This number does not include $108 billion in indirect economic impacts, nor $400 billion in "induced" impacts resulting from these activities. In this same year, aviation's total economic impact on the nation was in excess of $594 billion or about 5.6 percent of the gross national product (GNP). An example of the economic impact of several metropolitan airports is shown in figure 1 (ref. 5). On the other side of the capacity crisis, with increased growth and revenues, we have a dilemma between economics and environmental issues that particularly face the airport industry. In addition, there are other concerns related to the airport industry such as: acquisition and utilization of trust funds; spending of Airport Improvement Funds; Passenger Facility Charge; who really controls the airport--airlines or airport; and privatization of U.S. airports.

Critics have expounded on whether or not increased capacity will be needed at airports, in the airways, and linking ground transportation systems (ref. 5). However, the fundamental issue that remains is not the needs of the air transportation system alone, but what are the required technologies and infrastructure to serve intercity travel needs into the next century? Therefore, the present study of long-term airport capacity needs should be viewed in support of, and in cooperation with, initiatives and ongoing studies by the Federal Aviation Administration (FAA) and U.S. Department of Transportation (DOT) (refs. 1-6).

To determine the impact of technology on capacity improvements in the U.S. air transportation system and, consequently, to assess the areas where NASA's expertise and technical contributions would be the most beneficial, NASA funded the Massachusetts Institute of Technology (MIT) Flight Transportation Laboratory (NASA Langley Grant NAG-1-1149) to conduct a study focusing on these airspace and airport capacity issues. The outlook of the study was considered both near- and long-term (5 to 25 years). The MIT study, which is presented in reference 7, identified aircraft noise as the fundamental hindrance to capacity improvement. A summary of their major conclusions follows:

> 1. Community reactions to noise around airports ··· is the long term barrier to increasing the capacity of the nation's air transport system. More airports or vertiports must be built around major cities to accommodate the long term growth expected in air transport.
>
> 2. There are valuable returns from exploiting existing technology to reduce current Air Traffic Control (ATC) separation criteria used in Oceanic and Terminal areas.
>
> 3. There is a need to provide evidence of the economic, environmental, and operational viability of a Civil Tilt Rotor (CTR) Short Haul Air Transportation System to support decisions···to embark on a long-term CTR development program.

In an effort to acquire an independent assessment of the capacity problems and identification of possible technical solutions, the study purposely included interactions with the "users" outside of both agencies as well as with organizations within. The approach taken by NASA was that of actively working with the MIT Flight Transportation Laboratory during the interactions with these organizations. During the period of this study a large amount of material was generated and collected pertaining to the study conclusions, especially in the areas of aircraft noise and aircraft separation. This information includes details on the current state-of-the-art and trends for the technologies under investigation. Table 1 indicates the names of organizations with which interactions were held over a period of one and one-half years. They include aircraft and engine companies, airlines, port authorities, national and international organizations or associations, and government organizations.

This report expands upon and supplements the conclusions reached in the MIT study and includes assessments of the state of technology in those areas found to be critical to relieving congestion in the air transportation system and identifies improvements in technology that would increase capacity and reduce delays.

ACRONYMS

AAS	Advanced Automation System
ACCI	Aircraft Association Council International
ADS	Automatic Dependent Surveillance
ALPA	Airline Pilots Association
AOPA	Aircraft Owners and Pilots Association
ASTA	Airport Surface Traffic Automation
ATA	Air Transport Association
ATC	Air Traffic Control
ATMS	Advanced Traffic Management System
ATOMS	Air Traffic Operations Management Systems
CARD	Civil Aviation Research and Development
CNS	Communications, Navigation and Surveillance
CTAS	Central Tracon Automation System
CTR	Civil Tilt Rotor
db	Decibel
DNL	Day-Night Sound Level
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level
EVS	Enhanced Vision System

FAA	Federal Aviation Administration
FMS	Flight Management System
FY	Fiscal Year (October 1 through September 30)
GNP	Gross National Product
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
HBPR	High By-Pass Ratio
HSCT	High Speed Civil Transport
HUD	Heads Up Display
IAT	Interarrival Time
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rule
ILS	Instrument Landing System
IRU	Internal Reference Unit
MLS	Microwave Landing System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NRC	National Research Council
nmi	Nautical Miles
ODAPS	Oceanic Display and Planning System
PIAT	Partnership for Improved Air Travel
RPM	Revenue Passenger Miles

ROT	Runway Occupancy Time
RSU	Runway Sequencing Unit
SDRS	Standardized Delay Reporting System
SLST	Sea Level Static Thrust
TCAS	Traffic Alert and Collision Avoidance System
TMS	Traffic Management System
TRB	Transportation Research Board
VFR	Visual Flight Rules

SYSTEM CAPACITY AND TECHNOLOGY

During the interactions and discussions held with senior staff of the organizations listed in Table 1, emphasis was placed on their opinion or concerns regarding capacity and demand, and what should be done to address improvements required to reduce congestion and delays through technology. In general, comments ranged from "not a problem" to "impossible" and from "pour more concrete" to "improve utilization and techniques." However, by a large majority, it was concluded that air transportation capacity was an overwhelming problem world wide. The major areas requiring improvements through technology that were repeatedly heard in the interviews are as follows:

1. Aircraft noise reduction
2. Heads up Display (HUD) and enhanced vision systems
3. Separation between aircraft
4. Global Positioning System (GPS)
5. Runway Occupancy Time (ROT)
6. Traffic Alert and Collision Avoidance System (TCAS)
7. Situation display in cockpit
8. Wake vortex
9. Taxiways
10. Runway conditions
11. Systems integration
12. Flight Management Systems (FMS)

13. Weather forecasting and readout
14. Air Traffic Control (ATC) automation
15. Departure efficiency
16. Route structure
17. Large subsonic aircraft
18. Center Tracon Automation System (CTAS)
19. Microwave Landing Systems (MLS)
20. Safety and blunder

After consideration of the above list of individual capacity improvements along with a survey of the literature, the question arises as to whether we can quantify the individual effects of technology towards improvements in capacity. Obviously, a total system integration of the individually recommended technologies is required for the final assessment of capacity improvement. The economics of developing new technology and implementation of improvements will certainly have to be considered in the overall solution process to improve capacity.

FACTORS AFFECTING CAPACITY AND DELAY

A major concern to both airport operators and users is delay (refs. 8 and 9). At busy airports, delays in flight arrivals and departures begin to accumulate during the day due to the queue of aircraft awaiting their turn for takeoff, landing, or use of taxiways and gates at terminal buildings. These delays translate into increased operating costs for the airport users and wasted time for passengers. The cause for delay is often referred to as a "lack of capacity." In general terms, this means that a given airport does not have facilities (runways, taxiways, or gates) in sufficient numbers to accommodate all those who want to use the airport at peak periods of demand.

Capacity generally refers to the ability of an airport to handle a given volume of traffic (demand), and may vary with time depending on physical and operational factors that include airfield and airspace geometry, air traffic control rules and procedures, weather and traffic mix (refs. 4, 9, and 10). For a given airport configuration, there is a limit that cannot be exceeded without incurring an operational penalty. The successful management of an airport involves devising ways to compensate for those factors that, collectively, interact to decrease capacity or induce delay.

Delays occur on the airfield whenever two or more aircraft seek to use a runway, taxiway, gate or any other airside facility at the same time. With increased traffic density and request for service, the average delay increases exponentially as demand approaches airport capacity. When demand exceeds capacity, there is an accumulation of aircraft awaiting service that is directly proportional to the excess of demand over capacity.

The FAA Standardized Delay Reporting Systems (SDRS) is reported by three airlines and accounts for any delay in excess of 15 minutes as opposed to major delay as measured by the Air Traffic Operations Management System (ATOMS) (ref. 4). The SDRS defines delay relative to the following phases of flight: Taxi-in; Taxi-out; Airborne; and Gatehold. The FAA reported (ref. 4) that in 1988, nearly 80 percent of all flights were delayed 1 to 14 minutes in taxi-in or taxi-out. More delay occurred during the taxi-out phase than any other phase. Only 5 percent of flights were due to gatehold delay

It was reported (ref. 4) that there were 25 million operations in 1988 at the nations top 100 airports. By considering only an average airborne phase delay of 4.4 minutes per aircraft, there was a total of over 0.9 million hours of delay, which, at an estimated $1600 per hour, cost the airlines $1.4 billion. Figure 2 shows the estimated annual cost of delay to air carriers that was determined by multiplying the total operations and delay phase results (ref. 4) taken at the nations top 100 airports by the direct operating cost (DOC) per hour to the airlines. In a different view, 20,000 hours of flight delay translates into over $32 million annually at the cost of $1600 per aircraft per hour of airport delay.

The indicated trends (fig. 2) and forecast (ref. 4) suggest that, in the absence of capacity improvements, delay in the system will grow and the cost to airlines may double from about $5 to $10 billion between 1990 and 2000.

In the present study it was determined that today's capacity problems relate directly to all the previously mentioned physical and operational factors. These capacity issues will be briefly discussed.

Weather Conditions

For a given airport, the capacity is usually the highest in clear weather and maximum visibility. The existence of fog, low ceilings, precipitation, strong winds or wind shifts, and accumulation of ice and snow on runways can cause alternate operational changes to meet safety and

ATC procedures and severely reduce capacity. Even at large airports, with multiple runways and patterns at their disposal, some of the configurations may have a substantially lower capacity than the others. For most airports, it is the combined effect of weather, runway configuration, and ATC rules and procedures that result in the most severe loss of capacity or longest delay times. The U.S. airlines rejected the idea of limiting schedules to bad weather conditions. Their schedules are generated based on good weather conditions, which seems to occur most of the time, even though the primary cause of delay is weather.

The influence of weather declined from 1988 to 1989 (fig. 3), but was attributed as being the primary cause of 57 percent of the nations airport operations delay by 15 minutes or more on 391,000 flights in 1989 (ref. 4). Terminal air traffic volume increased and accounted for a record 29 percent of delays, while air traffic control (ATC) center volume was 8 percent. Runway construction was the cause of 3 percent of delay, National Airspace System (NAS) equipment interruptions for 2 percent, and 1 percent for other causes.

Airport Utilization /Scheduling

The FAA (ref. 4) has identified 27 major air traffic hubs in the U.S. as being the busiest for national and international markets, as shown in figure 4. There are 36 airports that handle 360 million passengers annually, which represents about 73 percent of the total enplanements in 1989. Origin of the traffic at each of the hubs shown on figure 4 is illustrated in the enclosed box at the lower left hand corner. A close observation of the individual hubs will indicate that, on the average, nearly 45 percent of all traffic is a result of transfers mainly being fed into or out of the hub by commuter traffic over short distances. The main point to be made is that the current lack of capacity in the U.S. exists at these major hubs.

A major cause of delay is flight scheduling. Certain arrivals and departure times are preferred by travelers, and are subsequently scheduled by the airlines. This peaking of demand, however, produces system overloads, traffic queues, et cetera, that lead to delays at originating and connecting points within the airport and airspace network. Traffic peaking has increased markedly since airline deregulation. For a given airport, there exists peak hourly demand conditions for services. Some airports are always near peak conditions and/or constrained by the number of available slots (for example, New York's La Guardia; Washington's National; Chicago's O'Hare; and London's Gatwick). Figure 5 shows an example of the passenger aircraft movements with time of day for New York's J. F. Kennedy Airport. For the particular day of the week shown, the net peak (shown as the number of aircraft on the ground) is seen to decrease from a level of about 50 at around 8 o'clock in the morning to essentially zero at noon, then rapidly peak at about 110 movements around 5 o'clock in the evening before decreasing again. Deliberate "peaking" of daily schedules, to create "connecting complexities" through regional hubs, have been designed by the airlines to maximize utilization of their airplanes under good weather conditions for both U. S. and international flights. Airport hourly capacity will also vary strongly with weather. Thus, when the weather deteriorates from conditions of operation under Visual Flight Rules (VFR) to those of Instrument Flight Rules (IFR) and near peak demand conditions, the number of arrivals and departures at various airports fall below that scheduled.

Airports and Runways

A special working group was formed under the TRB/NRC airport network study panel (ref. 6) to review and select existing economic models, demographic projections, and aviation forecasting techniques in order to obtain an approximation of future demand for air travel. Results from this study were reported in 1988 and (Appendix A, of ref. 6) are shown in figure 6 for a range of estimates under various input assumptions about Gross National Product (GNP), air fares, population growth, economic conditions, and travel propensity. The range of air travel demand under various scenarios is seen to reflect uncertainties inherent in extended projections from 1990 to 2050. For example, the revenue passenger miles (RPM) is forecast to double in the U. S. by the next decade from about 300 to over 600 billion for an assumed low GNP and high fares while for this same period it is projected to increase by a factor of about 5.5.

During fiscal year 1989, the number of airline flight delays in excess of 15 minutes was reported (ref. 4) to have increased at 12 of 22 major airports compared to the previous year. The percentage of flights delayed at these airports ranged from 0.1 to 10.3 percent. In 1988, 21 airports each exceeded 20,000 hours of airline flight delays. With no improvements in airport and airspace capacity (ref. 4) between 1989 and 1998, 41 airports in the U.S. are forecast each to exceed 20,000 hours of flight delays, 15 airports will experience 50,000 to 100,000 hours of delay, and four airports are forecast to exceed 100,000 hours of delay (fig. 7).

New Hubs: most of the traffic in the airport network is concentrated at relatively few airports where airline routes converge. As a result, the lack of capacity at these hubs increases delay. A possible solution would be to establish the future new hubs at existing conveniently located points. The FAA has identified a number of airports with underused capacity that could relieve a large number of overly congested airports now used as major airline hubs (ref. 4) and are shown in figure 8.

Airport Slots: in 1969, the FAA imposed a high-density regulation making Kennedy, La Guardia, Washington National, and O'Hare airports subject to slot allocation under VFR conditions. This regulation allows airlines to profit from sales of slots (utilized or not) originally allocated to them through scheduling committees but handed over to the airlines in 1986 when the buy/sell rule took place. Most new entrant airlines must pay exorbitant prices for available slots and oppose the high-density rule, and would welcome its elimination.

New Airports and Runways: for years, industry experts have claimed that the lack of airport expansion has been the main cause of our nations capacity problems. The FAA's testimony before the House Aviation Subcommittee in 1990, indicated that the major problem the nation faces in aviation today is congestion and delay at our airports that is forecast to grow, placing added strain on the air transportation system and cost to operators and travelers. While airport capacity is difficult to determine, it can be rationalized by comparing throughput (the number of operations, or arrivals and departures actually conducted) with demand, the number of aircraft seeking service, per day. Figure 9 shows the operations activity in 1988 for various types of aircraft and projected excess capacity requirements for the top 50 U.S. airports by the year 2000 (ref. 11). The results indicate that over this period of time, the total number of operations per day by all types of aircraft is expected to increase by 34 percent and the required excess capacity is about 22 percent.

At many of the existing congested airports (fig. 7), increases in capacity could be accomplished by the addition of some combination of new and extended runways or taxiways and associated changes in air traffic control procedures. Such additions and changes, which are highly site specific, would increase the hourly aircraft service rate both under VFR and IFR conditions. The FAA (ref. 4) has identified 400 projects and proposed new and extended runways for 66 of the top 100 airports in the U.S., for capacity increases by the year 2010. The total anticipated cost of completing only the new runways and extensions is about $6.5 billion by the year 2010.

Construction of new airports and runways are the most direct and short term actions that can be taken to improve airport capacity (refs. 1 and 4), especially in areas where current and future centers of business, commerce, and tourism will be important. Figure 10 lists the major airport expansion programs around the world. Studies (ref. 1) indicate that building 10 major new airports in the U.S., in densely populated and highly developed urban areas, will provide a capacity increase of 9 million operations annually by the year 2000 or the equivalent of 30 percent of all commercial air carrier movements in the country. Large capacity increases, both under VFR and IFR, can come from the addition of new runways properly oriented to allow independent arrival or departure of aircraft. The resulting increase in capacity has been reported (ref. 4) to range from 33 to 100 percent (depending on whether the baseline is a single, dual, or triple runway configuration).

Enhanced IFR Operations: if it were possible to achieve the equivalent of VFR operational rate except during severe weather conditions, it has been reported (ref. 1) that the hourly IRF rate at a typical hub airport (fig. 11) might be increased by 40 to 60 percent. This area will require new technology and will be most effective if implemented on a nation-wide basis.

Civil Tilt Rotor (CTR): construct new tilt rotor air transport system. Studies (ref. 12) have shown that about 40 percent of all commercial flights arriving at the 10 busiest airports are from distances less than 300 miles. These flights are mostly regional carriers, with passengers transferring to long-haul aircraft, and occupy the same gates and runways. While the CTR system could free up gates and runways by building vertiports that may produce a 10 percent capacity increase (ref. 13), there remains economic and technical issues to be resolved. The technical issues include community noise, human factor-based pilot controls, airspace navigation, vehicle drag/download, and rotors.

MAJOR CAPACITY CONSTRAINTS

In analyzing the overall findings of the MIT study of reference 7, there were two major themes that continued to emerge as constraints to the many issues and challenges facing airports in the U.S. National Airspace System:

First, there exists severe local political opposition to airport expansion due to noise from subsonic jet transport aircraft takeoff and landings. Noise is considered the Achilles heel of the airport industry and aviation system. The airport operator must find ways to reduce aircraft noise in response to local pressure. Noise not only affects millions of people, but costs airports far more than communities, travelers, and even the airport operators realize. FAA estimates "noise mitigation" will cost $1 billion per year for the next 5 years and localities will spend $20 billion to acquire land for noise buffer zones and airline purchases of new or hushkit aircraft (ref. 5).

Noise issues heavily impact air traffic control procedures. The airport must make a tradeoff between usable capacity and noise control, by restrictions on flight paths over sensitive areas during certain hours, with usual results being some loss of capacity or increase of delay. "We cannot hope to increase capacity unless we first tackle the noise issue," said Gary Letellier, Port of Seattle Deputy Director (ref. 5).

Secondly, operational procedures and air traffic control intended primarily for assuring safety of airspace and terminal traffic. These rules and procedures are basic determinants of capacity and delay by governing minimum allowable separations, runway occupancy, spacing of arrivals and departures, use of parallel and converging runways, and noise abatement and control procedures.

AIRCRAFT NOISE

Aviation is concerned with vehicles which, for the majority of their travel time, are well separated from local communities by vertical distances in terms of miles. Over most of their flight paths, they are the cleanest and quietest form of transportation. However, the aircraft noise problem is confined to regions around the terminal area. When jet aircraft first started flying out of major airports in the late 1950's, local residents expressed outrage. Since then, there has been those who have learned to tolerate the noise, but there remains sufficient and influential numbers who continue opposition. In the late 1960's, a Civil Aviation Research and Development (CARD) study (ref. 14) found aircraft noise in the vicinity of airports to be a major deterrent to the development of airports and growth of the civil aviation system in the U.S.. Today, noise is still a major impediment to airport expansion. Worldwide, there exists severe political and legal opposition to airports expansion due to jet transport noise. Thus,

the following discussions will attempt to address noise impact on the community and industry, forecast, and research needs.
Community Reaction to Noise: Many of the effects of noise on individuals are highly dependent on particular situations and cannot be generalized. However, past studies (refs. 15-17) have revealed that there are three primary direct effects: activity interference, annoyance, and hearing loss. Their statistical relationships to noise provide a quantitative basis for evaluation and control and are summarized by the Environmental Protection Agency (EPA) (ref. 15) and then later extended by the National Research Council (ref. 16). The two effects applicable to airport noise exposure are related to social activity interference (sound level and speech communications) and annoyance (extent of complaints and reactions to intruding noise).

The results of social surveys in several countries (refs. 18 and 19) have been combined to give a general relationship between long-term average outdoor day-night sound level (DNL) environmental noise (urban traffic, highways, railroads, and airports) and residential annoyance. Apparently, previous studies did not include sufficient input on dynamic changes in noise exposure, which can cause much stronger community reaction than expected. Figure 12 shows the expected annoyance and average community reactions to aircraft noise exposure (ref. 15). The results indicate that the degree of complaints vary between "none" and "vigorous" noise. The nonreaction response in the figure corresponds to a normalized outdoor DNL that has an average value of 55 db (not a regulation) which is 5 db below the 60 db level characterizing noise in a residential urban community (ref. 15), and is the reference for normalizing. A DNL of 65 db has been recommended by the EPA (ref. 15) as the maximum environmental noise level not to be a threat to public health and welfare, and accepted by HUD (ref. 20) and the FAA (ref. 21) to be normally compatible with all land uses including residential housing (Part 150 of the Federal Air Regulations).

There have been several studies in the past directed toward estimating the impact of noise from airport operations on neighboring communities (see, for example, refs. 22 and 23). The previous studies have indicated a rapid increase in the percentage of the nation's total population exposed to DNL values greater than 65 db, between 1960 and 1975, based on the national fleet (Stage 1 aircraft). Figure 13 (from ref. 24) is in agreement with the previous studies in that population exposure began to rapidly decrease after about 1975 to the present, as wide-body jets replaced narrow-body four engine jets (Stage 2 aircraft), while enplanements increased.

It should be noted (fig. 13) that the perceived decrease in exposed population to noise is expected to continue through the year 2000 when a majority of the older Stage 2 aircraft will be either retrofitted or retired to meet Stage 3 compliance. Even with the FAA's Airport Noise and Capacity Act of 1990 in effect (ref. 25), it is projected that about 0.5 million people will remain exposed to noise levels in excess of 65 db.

The regulatory guidelines for noise abatement flight procedures may be found in the FAA's Advisory Circular 91-53. While noise abatement procedures are being used as a means of complying with local airport noise limits, the impact of overall noise on the economics of reduced aircraft operations and derated-thrust takeoff procedures have not been reported. There are many options for aircraft noise abatement around airports to mediate the many complaints from local communities. In the late 1990's, for example, the Aircraft Owners and Pilots Association (AOPA) disseminated guidelines for GA pilots to reduce noise near airports. The practices involved flying at reduced power settings when below 2,000 feet altitude and on approach to the airport. It is felt by some, that neither the FAA's noise abatement options nor the AOPA-recommended flight procedures are widely used at airports. Further, decisions to change routing of flight paths over one community to another does not address the cause of aircraft noise. The Aircraft Noise Abatement Policy Act of 1991 (bill--H.R. 3639) calls for an Environmental Impact Statement (EIS) to be prepared when flight path changes are made below 1,500 feet (ref. 26). Figure 14 shows that most noise complaints are directed at flights within a 30-mile radius around the airport, which is the zone where most aircraft average 15,000 feet. FAA's current policy is to review only EIS's for route changes and operations below 3,000 feet.

The FAA (refs. 4 and 27) has indicated that there are more than 60 proposals in various stages of planning to either build or extend runways at major airports to increase capacity in the national aviation system. However, nearly all the proposals are being challenged by local residents claiming potential of injury due to increased noise levels. There are around 400 noise sensitive airports in the U.S. About 33 of these are considered noise impacted airports and are shown in figure 15. Nearly all of the airports shown are in densely populated areas. As indicated in the figure, the Air Transport Association (ATA) has estimated that there are about one million people across the nation that are affected by noise and 250 million suffering because of it. Figure 16 shows the major U.S. airports with night curfews enforced, based on individually applied noise restrictions, reflecting the perceived sensitivity of the local community to its noise environment. A growing number of airports are applying restrictions in the form of noise limits for takeoff and approach that are more stringent than FAA certification regulations.

Noise Policy: A new international noise policy toward operating restrictions on Stage 2 subsonic aircraft will require about half of the world's commercial aircraft now flying to be modified or phased out by the end of the year 2002 (ref. 28). Final noise rules issued by the FAA in September 1991 (fig. 17), indicate airline compliance requirements that differ from the International Civil Aviation Organization (ICAO) as reported in references 28 and 29. Figure 18 shows the maximum allowable noise level variation with takeoff weight under the FAA's FAR 36 Stage 3 compliance compared with noise data taken from reference 30 for various aircraft. The FAA rules (fig. 17) retain a 9-year deadline for eliminating Stage 2 aircraft, but permit airlines to use their older, noisier jets longer than planned depending on choice of a "phase-in" or phase-out" option. The ICAO noise policy attempts to compromise between airlines with large fleets of Chapter Three aircraft (designed after October 1977) and those with mainly Chapter Two aircraft. Community reaction to existing or anticipated noise exposure has resulted in local U.S. airport authorities developing their own use of nonstandard noise abatement takeoff procedures, airport access restrictions or night time operational limitations, and curfews that limit the choice of aircraft used by airlines (fig. 19). There is increasing concern on a worldwide basis that the U.S. practices dual-certification standards for aging aircraft to meet Stage 2 and 3 noise levels that allows operators to benefit from landing fee incentives or avoid airport-imposed curfews (ref. 31). As a result, German airports are planning to clamp down on airlines that declare Stage 3 noise compliance but actually generate Stage 2 noise levels.

Studies have shown (fig. 20) that about 45 percent of the total U.S. transport fleet (about $12 billion market value) consists of the older, noisier Stage 2 narrow-body aircraft (refs. 29, 30, and 32-34). Stage 2 aircraft also account for about half of the world's fleet (about $30 billion market value) with a declining resale value. Industry-wide cost estimates (between about $1 billion to $100 billion) for implementing the noise rules (fig. 21) vary widely depending on whether carriers fit hushkits to aircraft, re-engine them, or replace them with more expensive Stage 3 transports (refs. 32-34).

Noise Climate Projection: In 1988, about 25 million aircraft operations occurred at the nation's top 100 airports (ref. 4), accounting for 90 percent of all (459 million) airline passengers enplaned. By the turn of the century, operations are forecast to grow to 34 million at these same airports. Figure 22 shows the history and forecast (ref. 35) of the U.S. commercial transport aircraft requirement (ref. 27) to meet such a demand. The number of aircraft in the regional and major air carrier fleet are forecast to significantly increase over the next 10 years. Worldwide (not shown), the total commercial jet transport fleet is projected to nearly double (from about 8,000 to 15,000 aircraft) over this same period of time. The new deliveries represent tremendous export trade balance benefits based on an economic value of nearly $600 billion (ref. 35).

Through the turn of the century, community noise level exposure around most U.S. and European airports will decline steadily as an all-Stage 3 aircraft fleet replace Stage 2 aircraft (fig. 23). Based on an arbitrary 3 percent per annum growth in number of aircraft operations, community exposure to "significant aircraft noise" will be reduced by more than half (fig. 13) that in 1987 with an all-Stage 3 fleet by the year 2005. However, beyond this period, projected growth in air traffic will tend to erode the community noise reduction benefit achieved by the Stage 2 phase out. Thus, the worldwide air transportation industry may be approaching the crossroads where the Stage 3 fleet of aircraft has grown in number (and may exceed) to that of the older, noisier Stage 2 fleet. If this occurs, unpublished data by Douglas Aircraft Company indicate that the world Stage 3 fleet noise level trend (fig. 24) could eventually rise above Stage 2. As plans for retirement of the Stage 2 fleet are implemented, in compliance with FAR 36 Stage 3 (ref. 29), industry should examine the impact of future fleet growth. At the same time, research on aircraft noise reduction should be underway to provide the long range technology required and in anticipation of continued community pressure for quieter airplanes and need for expanded airport capacity.

Progress in Noise Reduction: The first step towards aircraft noise reduction was the introduction of the low by-pass turbofan engines in the early 1960's; however, they did not have a significant impact on noise reduction over earlier jet engines.

Between the mid-1960's and the early 1980's, there was a significant effort under the direction of the FAA and NASA to control aircraft noise along with industry and academia interaction. The basics behind current technology used to control noise was generated during this period. The NASA program funding support for aircraft noise reduction technologies during this period is shown in figure 25. As time passed and the environmental lobby became stronger and regulatory bodies (FAA and ICAO) generated noise requirements and certification rules, emphasis on design for low noise increased. When it became evident that industry could manufacture subsonic transports that meet FAR 36 Stage 3, government-sponsored noise reduction research was curtailed. The introduction of advanced high bypass ratio (HBPR) engines, which power today's wide-bodied Stage 3 aircraft, has improved the noise situation dramatically (fig. 26).

Impressive advances have been made in the reduction of engine noise source levels, particularly by the engine manufacturers. Figure 27 shows the variation in engine noise reduction resulting from improved turbomachinery (fan, turbine, compressor) and jet (exhaust flow, combustor) corrected to constant thrust (ref. 36). While the earlier very low bypass ratio (less than 3) engines were dominated by jet noise, current high bypass ratio (between 3 and 7) engines have nearly the same levels of turbomachinery and jet noise. Expectations for engines with BPR's greater than 8 are that advanced propfan noise levels will be approximately the same as current engines, and ultrahigh bypass ratio (UHBPR) engines will have low jet noise levels. Thus, it might be concluded that if, in the long term, the noise level target should emerge to be much lower than the current FAR 36 Stage 3 levels, it will possibly be achieved only through further improvements in engine technology and treatment and by reduced airframe noise.

Noise regulations are, to a great extent, established based on the technical feasibility of achieving desired noise reduction targets within a given time period. At future levels, aerodynamic or self noise of the airframe (direct function of weight and speed to the 6th power) will begin to dominate over engine noise. Furthermore, there is no real understanding as to what level of noise exposure will be acceptable in the future to communities surrounding airports or the economic benefits of reduced noise.

Areas For Noise Reduction Research

Airport Community Noise: The most important finding in the study of reference 7 was that, in the long term, airport community noise is the fundamental cause of lack of capacity in the U.S. National Airspace System (NAS) and the world's air transportation system. It should not be concluded that the airport noise problem will be solved totally by compliance of Stage 3 aircraft. While the technology challenge may be difficult to acquire, quieter aircraft will be needed to offset the adverse effects of increases in operations and to reduce costly restrictions at certain airports that are required for noise control. The research goals in this area should be directed toward:

1. Reducing aircraft source noise

2. Moderating airport community annoyance and reaction

3. Minimizing aircraft noise impact trajectories and airport community exposure

Aircraft Source Noise: The effort and magnitude of noise prediction methods and reduction technology that is needed to approach compatibility with anticipated community demands should include engine, airframe, rotor, and fan generated noise sources. Current transport aircraft (propeller and jets) as well as future advanced subsonic jumbo aircraft, civil tilt rotors (CTR), and high-speed civil transports (HSCT) should be considered. Concepts for active control of engine noise and novel techniques for suppression of propeller and rotor noise should continue to be developed. Development of improved prediction methods for airframe noise, jet and core noise, unsteady fan aerodynamics, and its integration with acoustic generation and propagation mechanisms should be continued.

There is a need to establish a reasonable set of international goals, below the current Stage 3 limits, for future transport aircraft noise acceptance and certification that are compatible for existing airports.

Moderating Annoyance and Reaction: Technology does not exist for forecasting airport noise environments and to assess community annoyance and reaction during times of new or significantly changing noise exposure. Research should be directed toward psycho-acoustic response of airport communities to both long- and short-term duration, level, and frequency of noise exposure. Other factors that should be considered include individual and community attitude toward the source of the noise, relationship between existing background noise and intruding noise, and the amount by which sound is attenuated from outside to inside of living and working space and interferes with normal communications.

Quiet, economic air transport systems can result only from an integrated effort by the aerodynamic, engine, and airframe designer in close coordination with the aircraft operator. Goals for the design of such new aircraft need to be established. Therefore, special attention and research should be given to low speed lift-to-drag ratio, maximum lift, number and location of engines, thrust-to-weight ratio, noise reduction due to thrust cutback, higher bypass ratio, optimum engine design for thrust, and required acoustic treatment.

Noise Abatement Flight Paths and Procedures: In order to meet airport noise restrictions, aircraft are being operated using nonstandard takeoff and landing procedures, and sometimes under strained safety margins that often result in reduced productivity and increased noise in other surrounding community areas. Research is needed to develop methods of operating aircraft, with advanced flight control and guidance systems, on various noise abatement trajectories for a single over-flight on a community.

Research is needed to establish the overall noise and economic impact of limiting the number of operations by commercial and cargo aircraft types (which is difficult under present legal constraints) or using derated-thrust takeoff procedures in an effort to meet airport noise limits.

AIR TRAFFIC CONTROL ISSUES

Over 100 major airports in three regions (Europe, Asia/Pacific, and USA) around the world have congestion problems and capacity enhancement that is becoming very urgent (ref. 37).

The Airport Association Council International (ACCI) has identified several basic strategies for providing additional capacity (ref. 37) by:

1. upgrading or the addition of new airport terminals and runways for independent arrival/departures under VFR and IFR,

2. improvements in airport automation and flight-systems management of demand for aircraft and passenger services,

3. reducing current IFR minimum separation distance requirement for dependent parallel and longitudinal runways, and

4. development of multiple approach concepts to permit simultaneous instrument approaches significantly reducing differences between IFR and VFR capacity.

Essentially all of these improvements in the ATC system, either directly or indirectly, involves reducing the separation criteria for safe operation under precision flight path capability. To achieve this capability with existing technology, there is a need to demonstrate their readiness for application. Some of the enroute and terminal area improvements are schematically illustrated in figure 28 along with definitions of technologies in figure 29).

Facilities Upgrade: Internationally, planned major airport expansion programs (refs. 9, 37, and 38), to meet forecast global market demands, are expected to total about $10.8 billion as previously shown in figure 10. These programs mainly include new terminals and runways. However, in Germany, for example, political and legal challenges have caused many delays and even cancellation of airport improvements (ref. 37). The new Munich airport opening in May 1992, was 30 years after planning start and could be their last. The final cost, including delay and environment impact mitigation, was expected to reach around $2.655 billion.

In the U.S., the FAA, airport operators, airlines, and other aviation industry representatives are co-sponsoring 24 individually located airport capacity design teams to analyze and develop solutions for capacity programs (ref. 3). These teams have developed more than 400 projects that include new airports and new and extended runways. Large capacity increases, under VFR and IFR conditions, can come from the addition of new or extended runways that are properly placed to allow additional independent arrival and departure traffic. Sixty-six of the top 100 U.S. airports have proposed new runways or extensions. The total anticipated cost of completing these new runways and extensions exceeds $6 billion (ref. 3). However, many of the projects have faced local community opposition who fear an increase in noise and other environmental degradation from new or expanded facilities. For example, the new Denver International Airport site (53-square miles) selection was in June 1986, at an estimated construction cost of $2.5 billion (ref. 39) with a projected operational date sometime in 1995.

Airport Automation: Currently, high construction costs and land use or regulatory constraints often outweigh the benefits of increasing airport capacity by expansion. Thus, in addition to global airport infrastructure upgrades and expansion to increase capacity, the FAA has plans for an Advanced Automation and Systems (AAS) integration services during the next 10 years. These plans are expected to create a $22 billion global market for industry to produce centralized computer-based automation and systems management solutions to handle more aircraft and passengers (ref. 40). The FAA, for example, estimates that total facilities and equipment funding needed for the years 1982 through 2000 is about $31 billion under its National Airspace System (NAS) Plan for modernization (refs. 41-42). The FAA's Advanced Traffic Management System (ATMS) plan for enhancing the ATC system focuses on using satellites for communication both in the cockpit and on the ground (ref. 43). The integrated terminal area and navigation systems are to be linked by data networks to central control facilities that will increase efficiency of operations and safety (refs. 40-64). Some examples of these automated concepts include:

1. Runway Sequencing Unit (RSU)--to optimize runway use and reduce air traffic controller workload.

2. Preflight identification system of passengers and baggage--to improve security.

3. Tagging airport runways, vehicles, and employees with high data-rate radar transponders--to improve controller display, track location, or movement.

4. Integrated security data concepts--to detect, screen, and control access of facilities.

5. Automated administration--to streamline billing, inventory, and purchasing.

6. Gate management--to enhance scheduling and utilization.

7. Airport Surface Traffic Automation (ASTA)--to detect and alert controllers and cockpit of collision.

8. Global Positioning System (GPS) or Global Navigation Satellite System (GNSS)--primary means for en-route, terminal, and transoceanic navigation.

9. Integrated GPS with Microwave Landing System (GPS/MLS) or with Inertial Reference (GPS/IRU) guidance--to improve both horizontal and vertical accuracy during Category 2 or 3 instrument landing.

10. Traffic-alert/Conflict Avoidance System (TCAS)--independent backup to the ground-based conflict detection system allowing flight crew participation in ATC operations and controller monitoring.

11. Oceanic Display and Planning System (ODAPS) or Automatic Dependent Surveillance (ADS)--allows aircraft to automatically transmit their location and altitude from on-board GPS/GNSS and/or IRU systems via data link.

12. Head-Up Display (HUD) with integrated Instrument Landing System (ILS) or Enhanced Vision System (HUD/EVS)--synthetic vision display during take off and landings and when weather deteriorates.

13. Center Tracon Automation System (CTAS)--to integrate both center and tracon automation for better sequencing of traffic on any track and flow management.

To effectively accomplish such automated concepts will require advancements in information technology systems and their application (refs. 65-67). For example, the FAA is currently applying 83 percent of the Department of Transportation's information technology budget to improve efficiency and safety (ref. 65). This effort by the FAA is essential for improved weather forecasting, preventing runway incursions, reducing ATC aircraft delays, and enroute over ocean reporting. NASA estimates it will spend about $1.85 billion on information technology in 1993--about 12.5 percent of its budget. The total federal budget in this area for 1993 is about $25 billion of which $15.5 billion will go to civil agencies. While some of the new systems were developed for the military and are off-the-shelf products, there is an increasing demand for open systems with network interoperability, software portability, and data interchange (ref. 65).

Some indicated benefits from these new systems are significant. Northwest Airlines estimates that using GNSS for en route navigation on its 747-400's could save more than $430,000 per aircraft in annual fuel costs as a result of "shortcut" flights (ref. 62). United Airlines estimates that about 5 percent of their operating cost is wasted for flights over the Pacific due to extra fuel burn required for typical 30-minute delays, waiting to get into crowded airspace on a route, or at an altitude that is optimum for reaching their destination (ref. 54). Thus, the added option of ADS position reports with GNSS should give the freedom to rapidly optimize flight paths instead of following preselected tracks.

A Flight Safety Foundation study postulates that HUD's could have prevented 31 percent of all civil aircraft accidents that resulted in total or major aircraft loss between 1959-1989 and 33 percent of the accidents that occurred on takeoff (ref. 61).

Separation Between Aircraft: Reducing aircraft IFR separation standards could have a significant impact on delay costs (ref. 68). Airport operators have indicated that aircraft separation criteria (fig. 30) for vortex considerations result in about a 15 percent reduction in airport capacity that amount to millions of dollars per year in cost. One of the more promising ways to improve the capacity of the ATC/Airport infrastructure is to provide more inter-arrival paths and spacing of aircraft on approach under IFR conditions (ref. 11). However, two major hurdles in the reduction of longitudinal separations on approach are the alleviation and avoidance of wake vortex hazards to following aircraft and runway occupancy.

When the wake vortex problem was recognized nearly 20 years ago, two efforts were undertaken. The FAA initiated a study of the vortex problem with a view towards minimizing the effects of wake turbulence as an impediment to air traffic flow without compromising safety. The study (ref. 11) defined a window at the ILS middle marker and about 3,000 feet from the runway threshold, beyond which the existence and duration of vortices would no longer present a hazard to trailing aircraft. This approach required the development of a wake vortex detection and avoidance system that has been moderately successful in characterizing wakes and development of meteorological ways to predict the presence and duration of wake vortices. While such a system has been proven technically feasible, it has not been operationally acceptable by some of the users. Around the same time period, NASA concentrated on the mechanics and causes of wake vortices and their research demonstrated the possibility of accelerating vortex dissipation and decay through the use of flaps and spoilers on heavy jets (ref. 11). These efforts have not reached the point where either the manufacturers or the users have implemented such wake vortex alleviation systems due to various aircraft performance penalties.

Reference 69 is an FAA advisory circular that indicates the hazards of aircraft wake turbulence and recommends related operational procedures. To allow sufficient time and distance for the safe dissipation of a wake vortex, the FAA has classified aircraft into three categories (heavy, large, and small) and specified that separation standards be used between successive aircraft on final approach as shown in figure 30. Since the initial intensity of the vortices varies directly with the amount of lift being produced, the heavier the aircraft, the stronger the vortices. Thus, the driving separation criteria becomes the heavy jet aircraft followed by a heavy jet (4 nmi) with an additional 1 and 2 nmi increase in distance required for in-trail large and small aircraft, respectively (fig. 30). The FAA further specifies that any aircraft taking off behind a heavy jet must be separated by at least two minutes. Consequently, the addition of heavy jets into the airport traffic mix increases the landing and takeoff intervals as well as the time to vacate the landing runway. An example of the average separation times (seconds) are shown in figure 31 for aircraft takeoff and landings with other traffic mix of equal large and small aircraft (ref. 11). From the results shown in figure 31, runway capacity has been computed (ref. 11) for various percentages of heavy jets and takeoff-landing rates in an equal mixture of large and small aircraft. The results shown in figure 32 illustrate the possible capacity increase with no heavy aircraft in the mix for a single runway.

The actual, achieved separations between aircraft may have a variance compared to the minimum values shown in figures 30 and 31 due to different skills of the pilots and controllers involved and the fact that no control is exercised inside the final approach fix. An example of the observed spacing recorded at O'Hare International Airport, and provided by the Airline Pilots Association (ALPA), is shown in figure 33 on runways approved for a 2.5 mile separation minima, under VFR with dry runways. At the far left of figure 33, separations of less than 40 seconds sometimes require the following aircraft to "go-around" to prevent two aircraft from being on the runway at once. At the far right, the runway is being underutilized between arrivals. For the case shown (fig. 33), the acceptance rate is 42 aircraft per hour based on arrivals only. The results indicate that precise control over the inter-arrival interval could peak the distribution at about 60 seconds and subsequently improve the maximum acceptance rate.

Depending on the degree of sophistication developed in TCAS and related equipment, for example, it is possible to achieve very substantial improvements in the spacing distribution and arrival rates as can be seen from a typical "miles-in-trail" chart (fig. 34) provided by ALPA. Considering the required spacing for different classes of aircraft (fig. 30), a ground speed of 180 knots at a three nautical mile spacing on figure 34 results in a minimal 60 second interval between aircraft. A combination of TCAS/FMS can be provided with displayed airspeed commands to be maintained, position of both aircraft in a pair, and position of the runway threshold. Thus, precise control of the interval may be maintained at the runway without compromising the final approach speed, occupancy margin, and throughput. As delays decrease and runway capacity increases, the potential benefit of this technology improvement can be large.

Since the wake vortex problem continues to be a major constraint to IFR capacity, and a detection and alleviation system has not been fully developed and accepted, cooperative program planning is underway between the FAA and NASA to provide the required technology. In general, the program includes new separation criteria (vortex encounter simulation and hazard validation), dynamic spacing methodology (vortex decay modeling and airborne or ground sensors for detection), wake alleviation and modification (high-lift design methods).

Both of these constraint issues will now be discussed in detail. In the mid-1980's, the Massachusetts Institute of Technology (MIT) Flight Transportation Laboratory conducted a study of the potential of advanced technologies on the ATC capacity of high-density terminal areas (ref. 70). The FAA recently initiated a study through the MITRE Corporation (ref. 11) to evaluate the potential increases in airport capacity through ATC system improvements in the airport and terminal area. In the study, runway configurations (single, dual, parallel), aircraft types, and demand characteristics were defined. Parameters that may be changed from a baseline as a result of some improvements in the ATC system were then varied and the FAA Airfield Capacity Model used by the MITRE Corporation to compute the increases in capacity under today's VFR or IFR operations (ref. 11).

The four aircraft classes assumed (ref. 11) in the FAA Airfield Capacity Model and parameter values representing today's VFR and IFR operations are summarized in figures 35 (a) and (b), respectively. Today's VFR and IFR capacities for three runways analyzed are shown in figures 36 (a) and (b), respectively, and represent baseline values from which computations of potential capacity increases were made. A summary of the effect on VFR and IFR capacity due to various reductions in the different parameters and operations are shown in figures 37 (a) and (b), respectively. In general, the results indicate that the largest percentage gains in capacity are through reductions in inter-arrival time and separations.

By setting the parameter values to be absolute minimums, an estimate of the theoretical upper bound of capacity increases was determined by MITRE (ref. 11). A more "realistic" upper bound on the potential for capacity increases was also determined by setting the parameters to intermediate reduced values. Figures 38 (a) and (b) show a comparison between the theoretical and future "realistic" upper bounds on capacity increases under VFR and IFR operations, respectively. The results shown are general and are based on ATC system improvements; actual capacity increases at specific airports will vary due to local conditions and external factors. "Realistic" estimates of the upper limit of VFR and IFR capacity increases (fig. 38) are on the order of 25 and 78 percent, respectively, depending on operation.

Figure 39 shows a summary of the estimates of potential increases (depending on the baseline runway configuration) in airport capacity through ATC systems improvements in the airport and terminal areas generated in the study by MITRE (ref. 11). The results indicate that the greatest increase comes from the addition of a new runway for independent arrivals/departures under VFR and IFR that is between 33 to 100 percent. The development of multiple approach concepts to permit simultaneous instrument approaches would significantly reduce the differences between IFR and VFR capacity that could result in a 44 to 100 percent increase in IFR capacity. Reduction in diagonal separation minimal requirement from 2 to 1 nmi for independent parallel operations could increase capacity by 25 percent and in longitudinal from 3 to 2.5 nmi (with 1 nautical mile reduction in other wake vortex separation rules) could increase capacity by 15 percent. Reduced variability in inter-arrival and runway occupancy times would increase capacity by 18 percent for VFR and 16 percent for IFR.

ALTERNATIVE AVIATION TRANSPORTATION SYSTEMS

More and more there seems to be an urgency to develop long-range plans that incorporate advanced transportation technology for the nation. These plans should include new or alternative forms of aircraft that would allow existing and future airport infrastructure to be used more efficiently (refs. 71-76). There are two types of aircraft that appear to offer promise for increasing capacity. One is through fewer but substantially larger size aircraft (refs. 71-73), and the second is aircraft with the capability of operating on shorter runways (refs. 74-76). Increasing the seating capacity of today's wide body jet aircraft by nearly a factor of two seems technically and economically feasible but has not appeared on the market. Such aircraft could be of significant benefit in terms of reducing runway utilization and operations, but may increase passenger congestion at the gates and in the terminal buildings. The real challenge may be that of economic compatibility between aircraft and airport designs that achieve the lowest system cost.

Recent surveys have shown that nearly half of all commercial flights (predominantly regional airlines) arriving at the ten busiest U.S. airports are from distances of less than 300 miles and typically occupy gates and runways in the same flow of traffic as long-distance aircraft. Northeast corridor studies conducted by Boeing (ref. 74) of the Kennedy, La Guardia and Newark airports, for example, has shown that a civil tilt rotor (CTR) system for short-haul operations could free up about 280 slots per day. This could increase capacity at these three airports by about 18 million passengers annually without additional runways or gates. A joint study by NASA and FAA projects development of a $2 billion tilt rotor system and urban vertiports on the East Coast by the year 2000 (ref. 75).

A comprehensive study (ref. 77) that included market and several potential transportation systems for the California corridor of the year 2010, concluded that advanced aircraft concepts and high speed ground transportation could meet the corridor needs. The nation's airport capacity and overall efficiency of the transportation system are only partly determined by infrastructure and how it is used. Aircraft characteristics, mix, utilization, and the technology employed to control their movement is an important part of the system performance. For example, extensive use of large wide-body aircraft on heavily traveled routes would allow more passengers to be carried without increasing the number of aircraft. Aircraft capable of steep takeoff and landing might have a large impact on capacity as short-haul feeders replacing conventional aircraft now used.

Tilt rotor technology has a long history that began in the 1950's with the former National Advisory Committee for Aeronautics (NACA) and Department of Defense (DOD) with supported research that included advanced helicopters, tilt wings, tilt rotors, and direct jet lift. In 1989, the California Department of Transportation began an effort to evaluate the feasibility of tilt rotor aircraft to ease airport traffic congestion. In the meantime, early stages of development both in the U.S. and Japan, indicate the tilt rotor promises vertical lift performance of that for helicopters with the speed, efficiency, and payload capabilities of turboprop aircraft. Its main feature is two rotor wings attached to the fixed wing portion of the vehicle that are rotated in flight from the vertical upright to horizontal positions.

The commercial and economic potential for civil tilt rotors (CTR) may be significant in regions surrounding most congested urban airports.

Creation of vertiports at various locations within a 150-mile radius of a region's major airport could minimize delays, relieve congestion, reduce commuting time, and increase mobility at a lower cost to travelers. However, a CTR has unusual characteristics that raises the question of being commercially viable and there are issues of certification (refs. 7, 12, and 74).

SUMMARY

Information has been presented that supports the findings of a study conducted by the Massachusetts Institute of Technology focusing on airport and airspace capacity issues (ref. 7). That study found aircraft noise and aircraft separation to be the major issues causing air transportation system capacity problems. Material presented in this paper overviews the state-of-the-art in aircraft noise technology and aircraft separation technology as it affects capacity issues, and provides insight into directions for further research.

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Table 1. Organizations solicited in the aviation systems capacity study.

NASA Langley Research Center
NASA Ames Research Center/FAA Field Office
FAA Technical Center

General Electric	Massachusetts Port Authority
Pratt & Whitney	Port Authority of New York & New Jersey
Boeing	Federal Express
McDonnell Douglas	Northwest Airlines
Mitre Corporation	Olympic Airways
MIT Lincoln Laboratory	Swissair

Aerospace Industries Association of America
Airport Operators Council International
Air Transport Association of America
International Civil Aviation Organization
Flight Safety Foundation, Inc.
Airline Pilot Association
National Air Traffic Controllers Association

Economic Benefit of Metropolitan Area Airports

Metro Area	Economic Annual Activity	Annual Earnings	Jobs
	($Million)	($Million)	
New York City	30,312.7	9,747.2	405,045
Los Angeles	29,317.2	9,676.2	399,352
Chicago	23,189.9	7,731.4	367,626
San Francison/Oakland	19,049.0	6,299.6	257,164
Dallas/Fort Worth	13,246.6	4,237.9	211,164
Atlanta	10,915.1	3,786.4	169,932
Washington, D.C.	10,819.8	3,786.4	205,326
Miami	9,797.0	3,421.6	179,325
Denver	8,782.8	3,040.8	153,346
Houston	9,449.2	3,006.4	154,776
Seattle	7,559.5	2,518.5	131,363
St. Louis	6,837.3	2,266.4	124,363
Phoenix	6,090.6	2,125.2	129,728
Detroit	5,666.6	2,063.8	101,289
Boston	5,271.8	1,912.3	90,633
Minneapolis/St. Paul	5,290.8	1,863.0	90,633
Kansas City	5,116.2	1,703.7	92,133
San Diego	4,831.5	1,572.7	67,133
Philadelphia	4,350.3	1,475.4	75,973
Pittsburgh	4,000.4	1,376.0	67,783
Ft. Lauderdale	2,990.3	1,011.8	57,365
Baltimore	2,991.4	1,074.2	53,680
Cleveland	3,017.5	995.0	58,151
Salt Lake City	2,824.2	952.6	60,954
San Jose	2,668.5	864.1	37,439
Cincinnatti	2,305.6	776.7	42,818
New Orleans	1,705.3	528.5	30,958
Portland	1,619.7	548.9	35,985
Milwaukee	1,136.7	398.2	25,708
Buffalo	736.4	241.9	9,760
TOTALS:	241,890.6	80,856.4	3,887,466

Source: Partnership for Improved Air Travel

Figure 1. Example of the economic impact of several metropolitan airports in 1989.

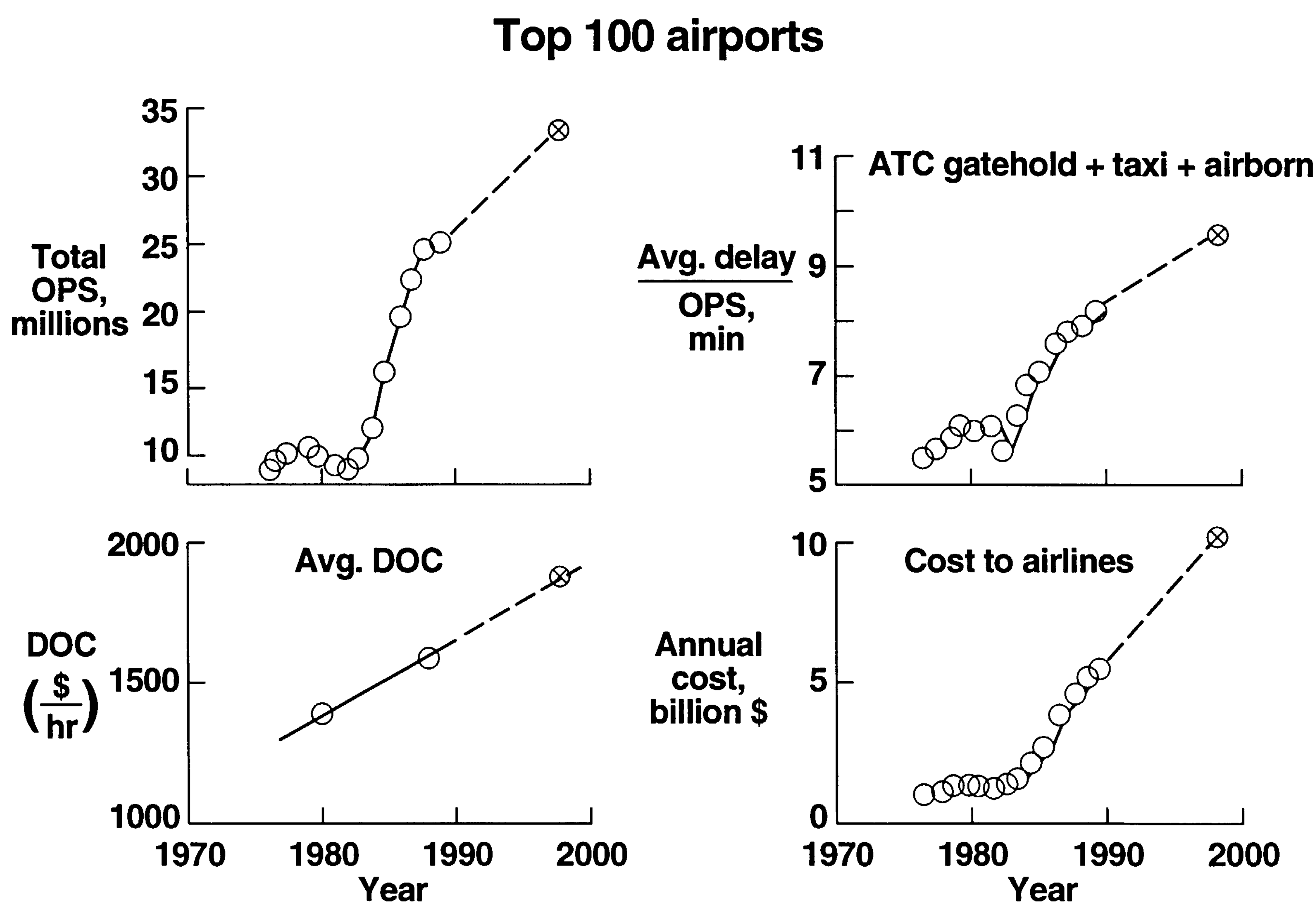
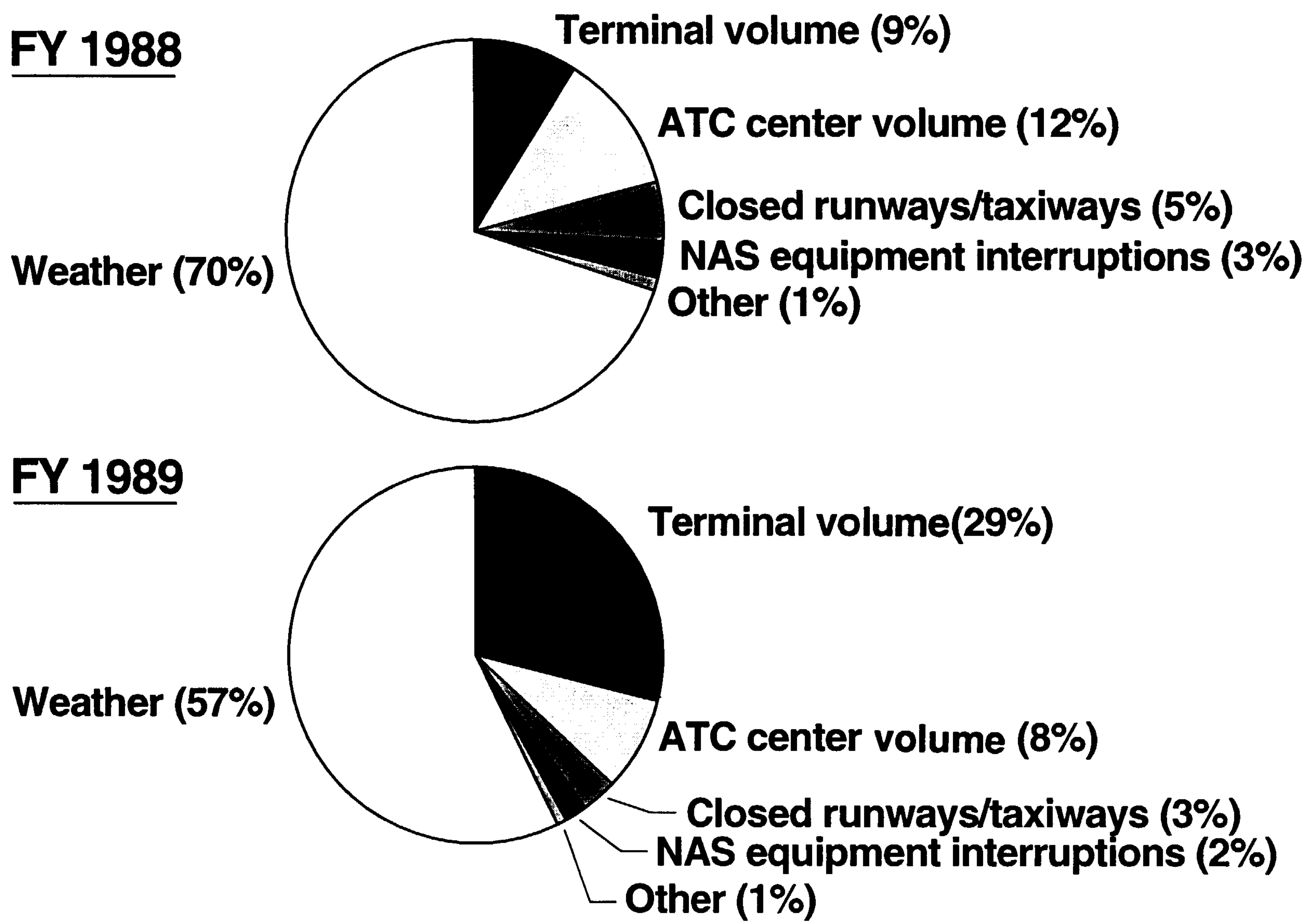
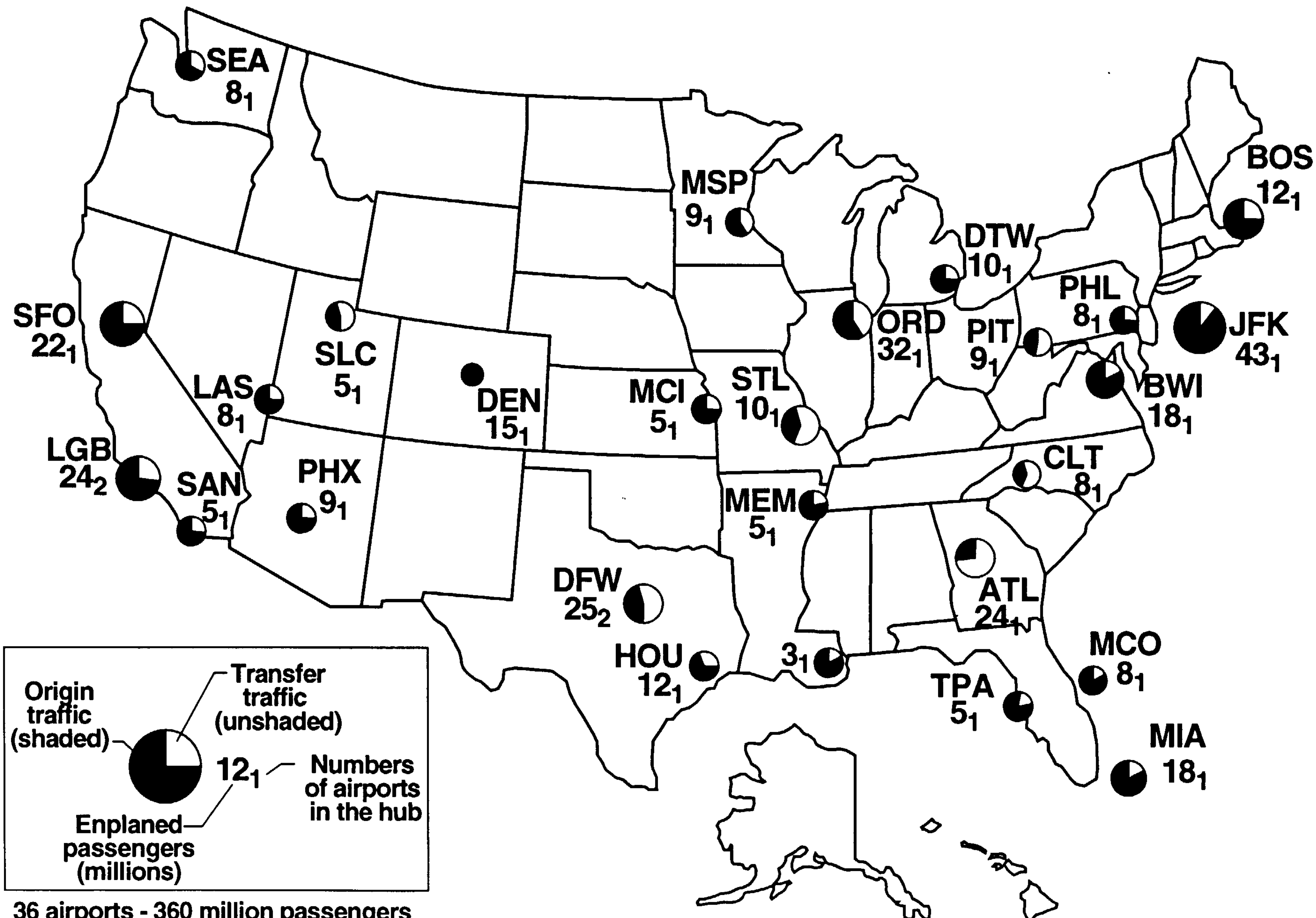


Figure 2. Estimated cost of delay to air carriers.



Source: ATOMS data
Ref. 1990-91 Aviation System Capacity Plan

Figure 3. Primary cause of delay of fifteen minutes or more in the U.S. National Airspace System (NAS).



36 airports - 360 million passengers
73% of total passengers

Figure 4. Busiest air traffic hubs in the U.S. for 1991.

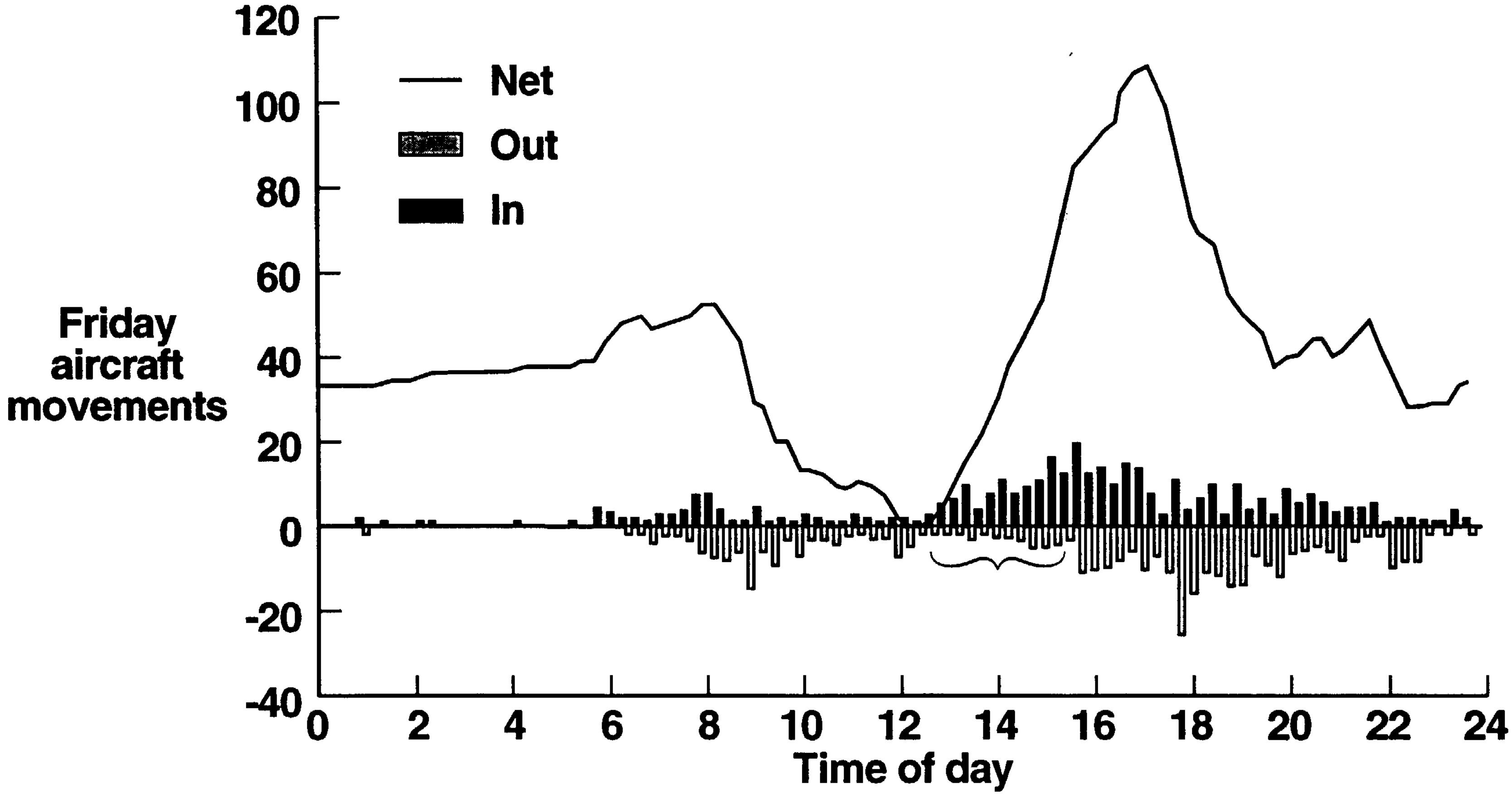


Figure 5. Example of passenger aircraft movements for J. F. Kennedy Airport.

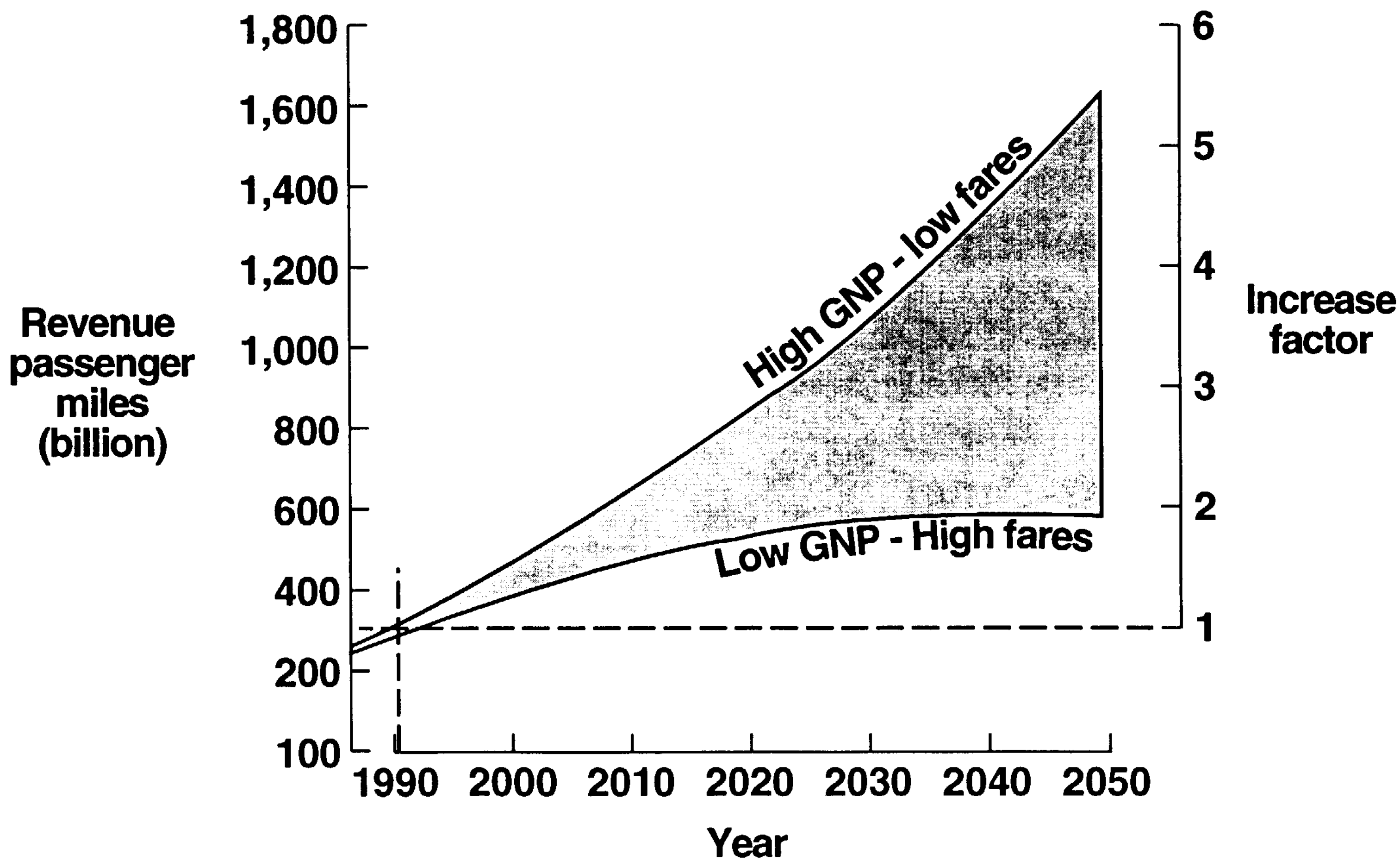


Figure 6. Projected U.S. air travel demand for several assumed economic scenarios.

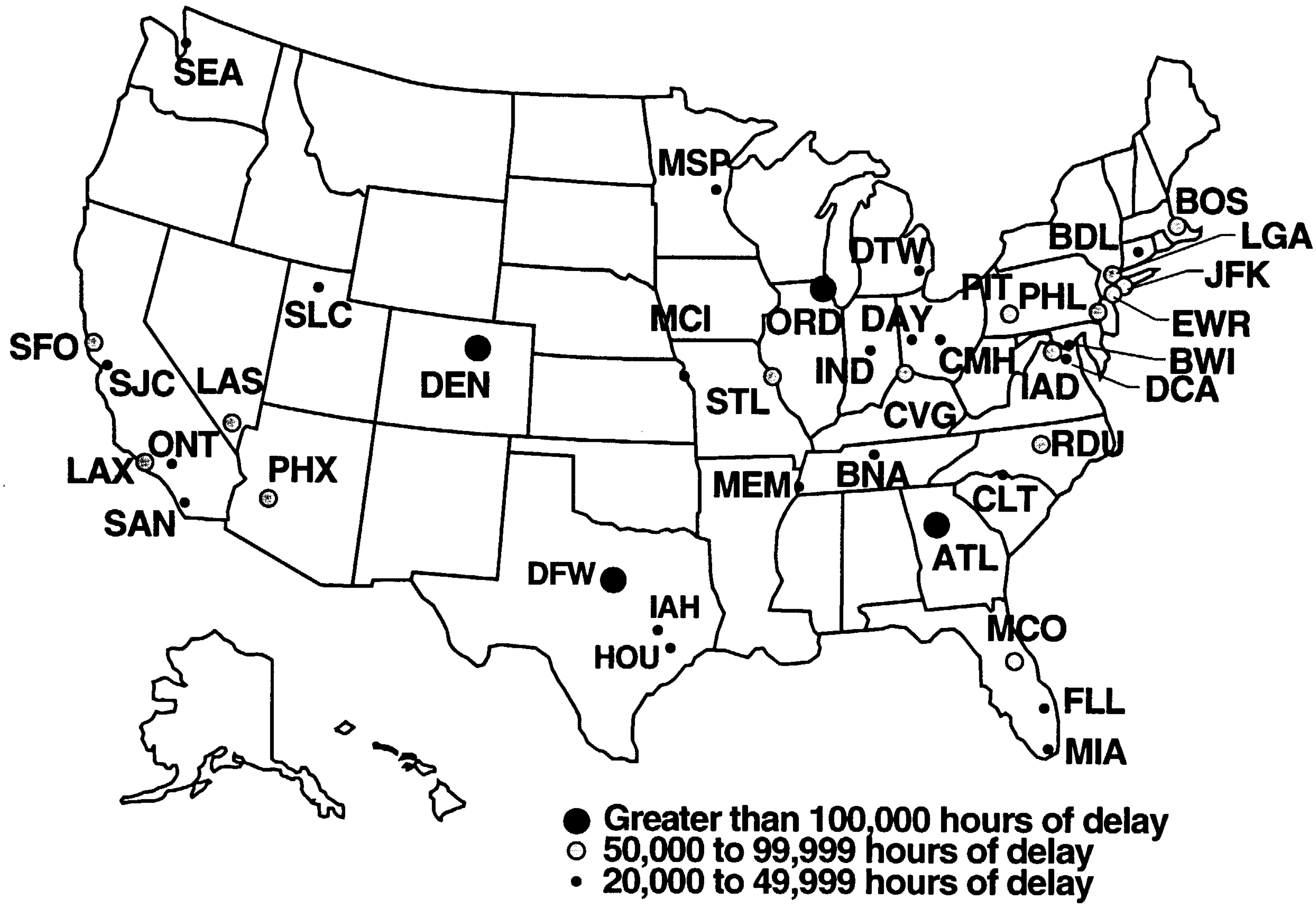


Figure 7. Airports exceeding 20,000 hours of annual aircraft delay in 1998 assuming no capacity improvements.

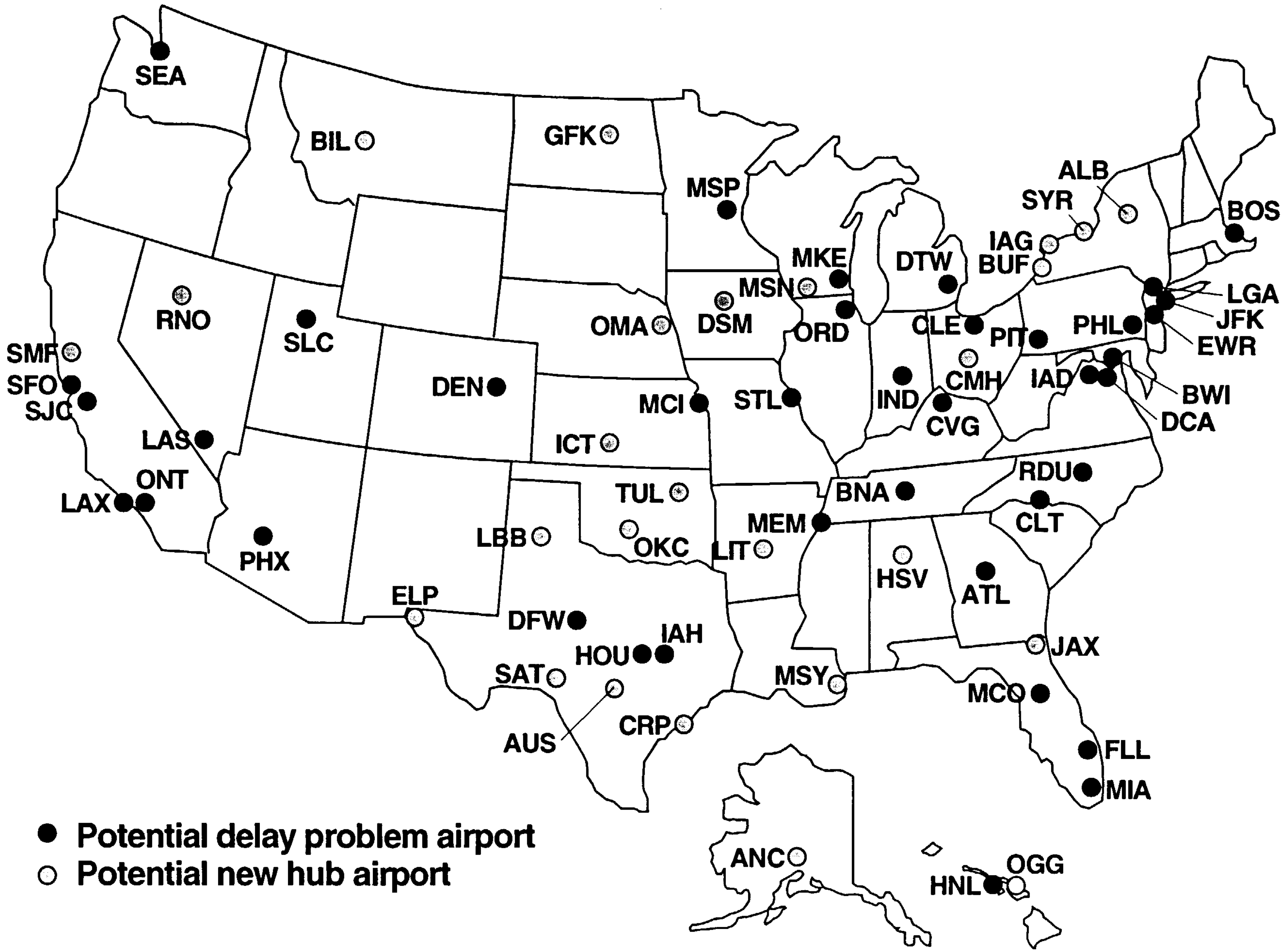
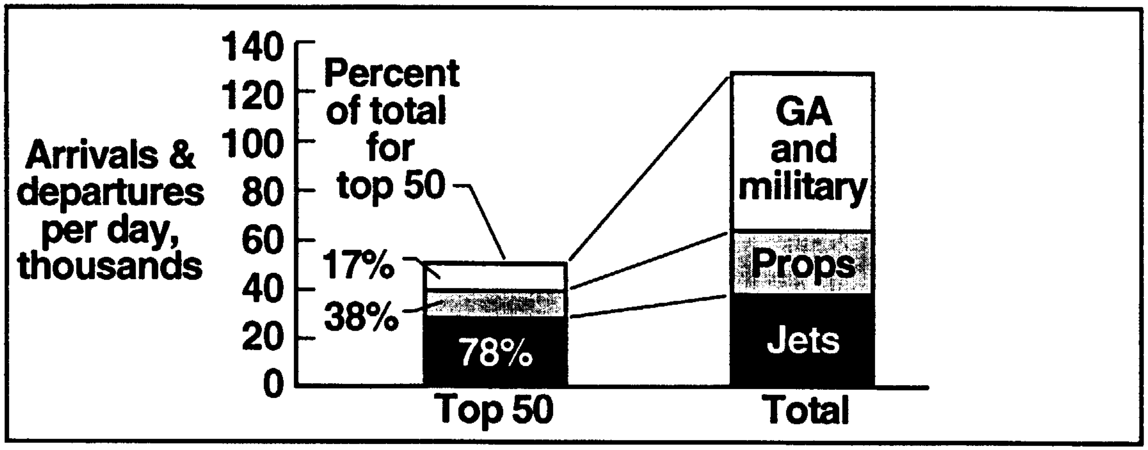


Figure 8. Potential new connecting hub airports having dual IFR approaches located more than 50 miles from 1998 potential delay problem airports.

U.S. AIRPORT ACTIVITY



TOP 50 U.S. AIRPORT ACTIVITY

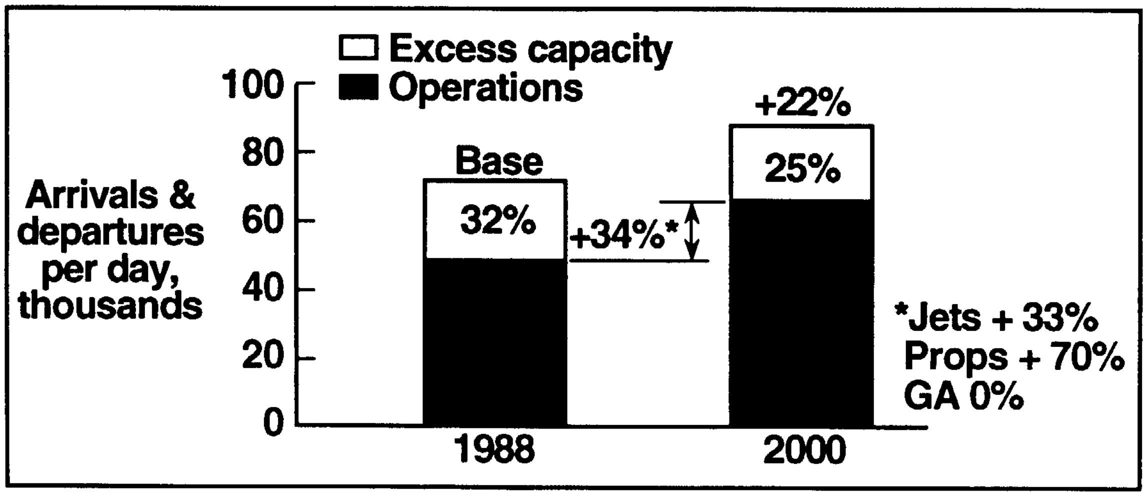


Figure 9. Comparison of top 50 U.S. airport activity in 1988 and projected excess capacity by year 2000.

City/Airport/Country	Project	Cost (US $M)	Completion	Passengers in 1990
Franfurt-Rhein Main, Germany	New terminal & other facilities	$4,440 M	1994	29.6 M
London-Stansted, UK	New terminal	750M	1991	1.2 M
Kaohsiung, Taiwan	New terminal & other facilities	550M	1994	N/A
Louisville-Standiford Field, USA	New parallel runway	500M	1995	0.95 M
Hamburg-Funisbüttel, Germany	New terminal complex	480M	1993 (Phase I)	6.9 M
Jakarta-Soekarno Hatto, Indonesia	Three new terminals	350M	1991	7.95 M
Las Vegas-McCarran International, USA	New terminal & runway	300M	1991	18.6 M
Berlin-Tegel/Schönefeld	New terminal & runway expansion proposals	600M	1995	8.7 M
Melbourne-Tullamarine, Australia	Terminal expansion	256M	N/A	8.55 M
Philadelphia-International, USA	New terminal proposed	250M	N/A	16.3 M
Manchester-International, UK	New terminal & other facilities including raillink	215M	1993 (Phase I)	10.8 M
New Orleans-International, USA	Terminal & runway extension	200M	1991	7M
Istanbul-Ataturk International, Turkey	New terminal	200M	1992	6.5M
Balikpapan, Borneo, Indonesia	Terminal & runway expansion	200M	1994	0.75M
Oakland-International, USA	Proposed new runway	143M	N/A	2.2M
Sydney-Kingsford Smith, Australia	Third runway proposal	175M	N/A	12.2M
Warsaw-Ocecie International, Poland	New terminal & cargo centre	155M	1992	2.7M
Nykoping-Skavsta, Sweden	New terminal & runway improvments (former Air Force base)	140M	N/A	N/A
Düsseldorf-International, Germany	New runway & terminal extension cargo building & hangar	175M	1992	11.95M
Fort Myers-SW Florida Regional, USA	Terminal & runway extension	130M	1992	1.6M
Atlanta-Hartsfield International, USA	Fifth parallel runway	130M	1994	48M
Stuttgart-Echterdingen, Germany	New terminal	120M	N/A	4.4M
Memphis-International, USA	New runway	105M	1994	8.9M
Dallas Fort Worth, USA	New runway	100M	1993	48.5M
Tulsa-International, USA	New parallel runway	100M	1998	3.2M

Interavia Aerospace Review June 1991

Figure 10. Major airport expansion programs (in excess of $100 million).

Figure 11. Major U.S. airport hubs for 1991.

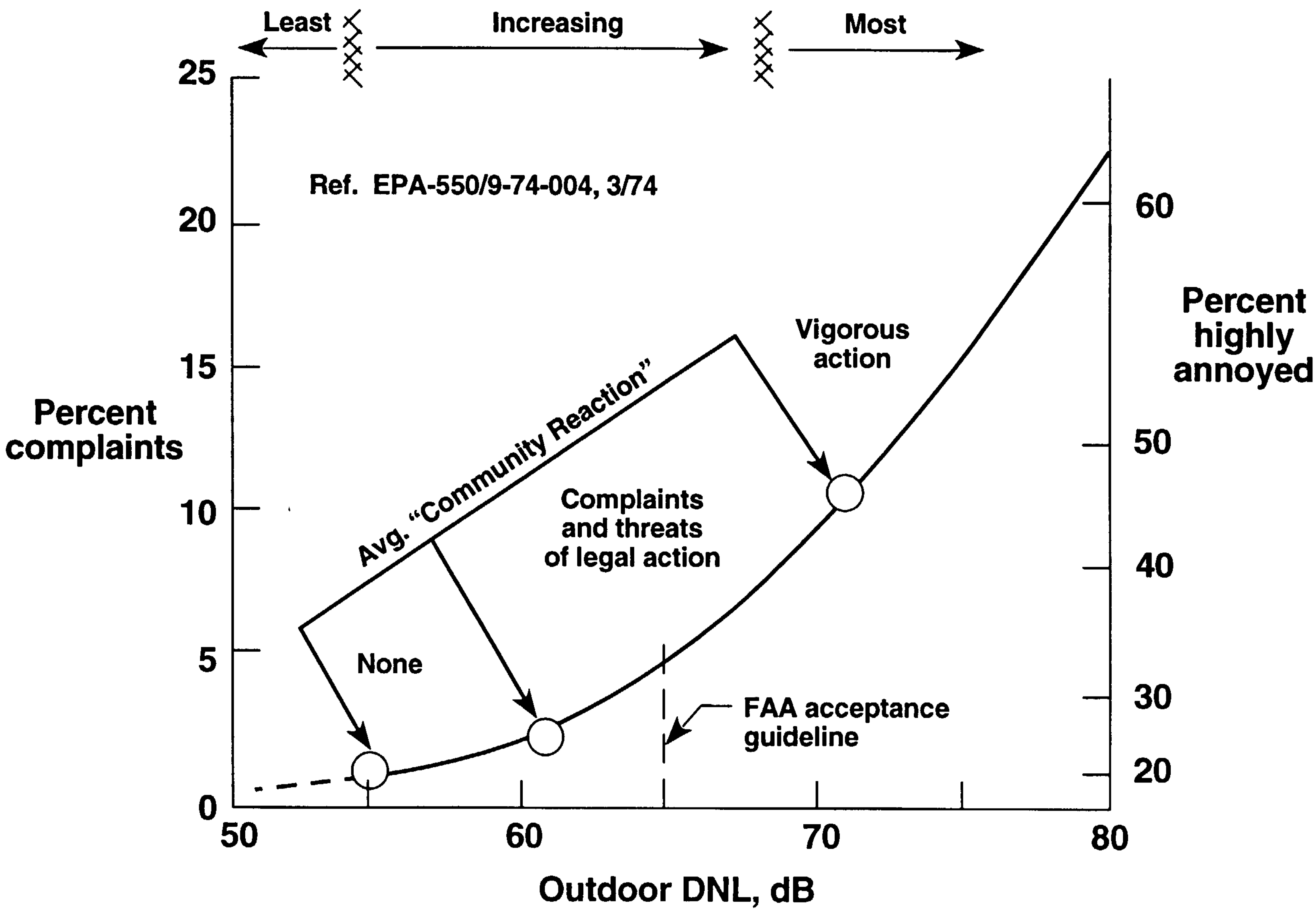


Figure 12. Expected annoyance and community reactions to aircraft noise exposure.

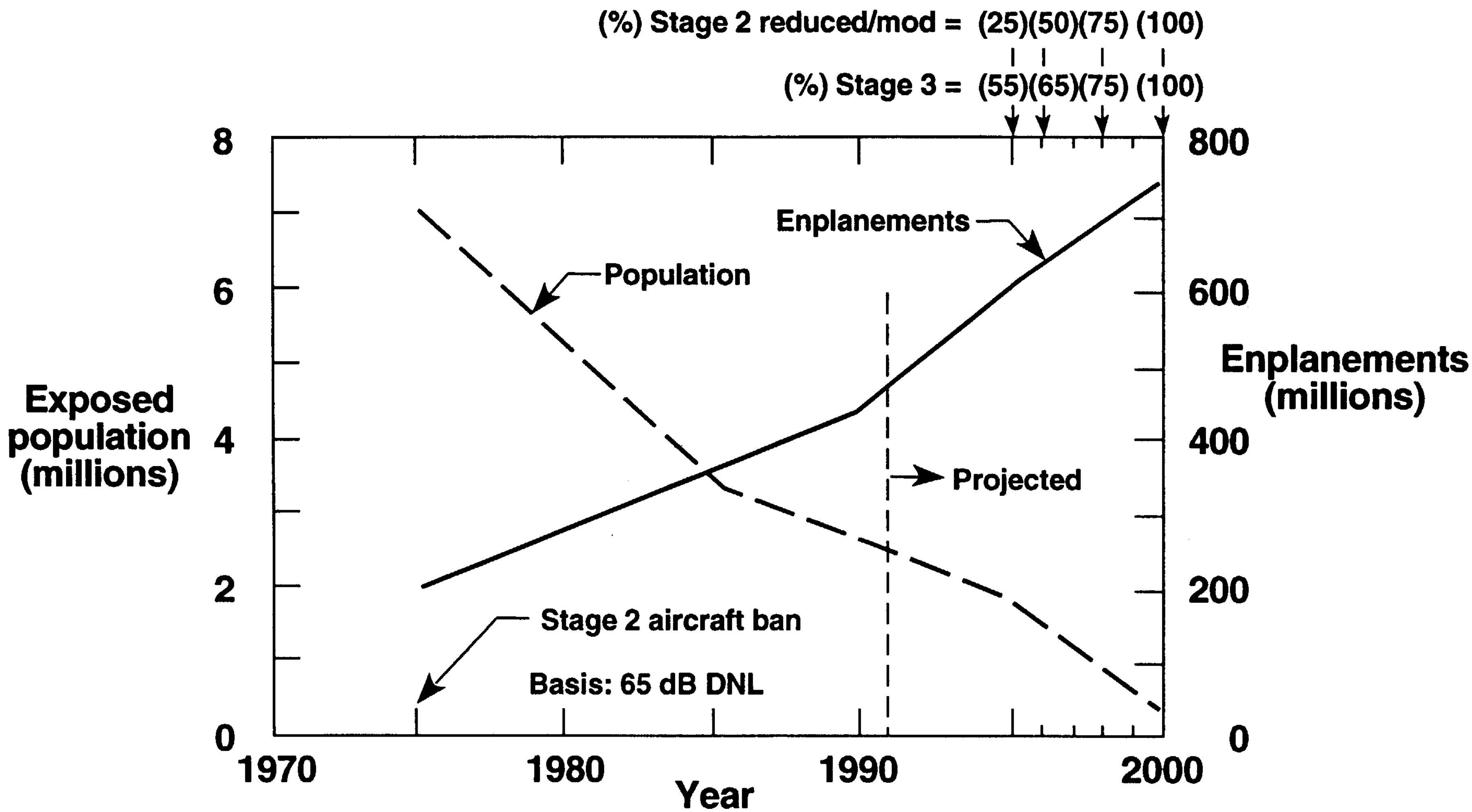


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Figure 13. Population exposed to noise due to stage 2 aircraft ban.

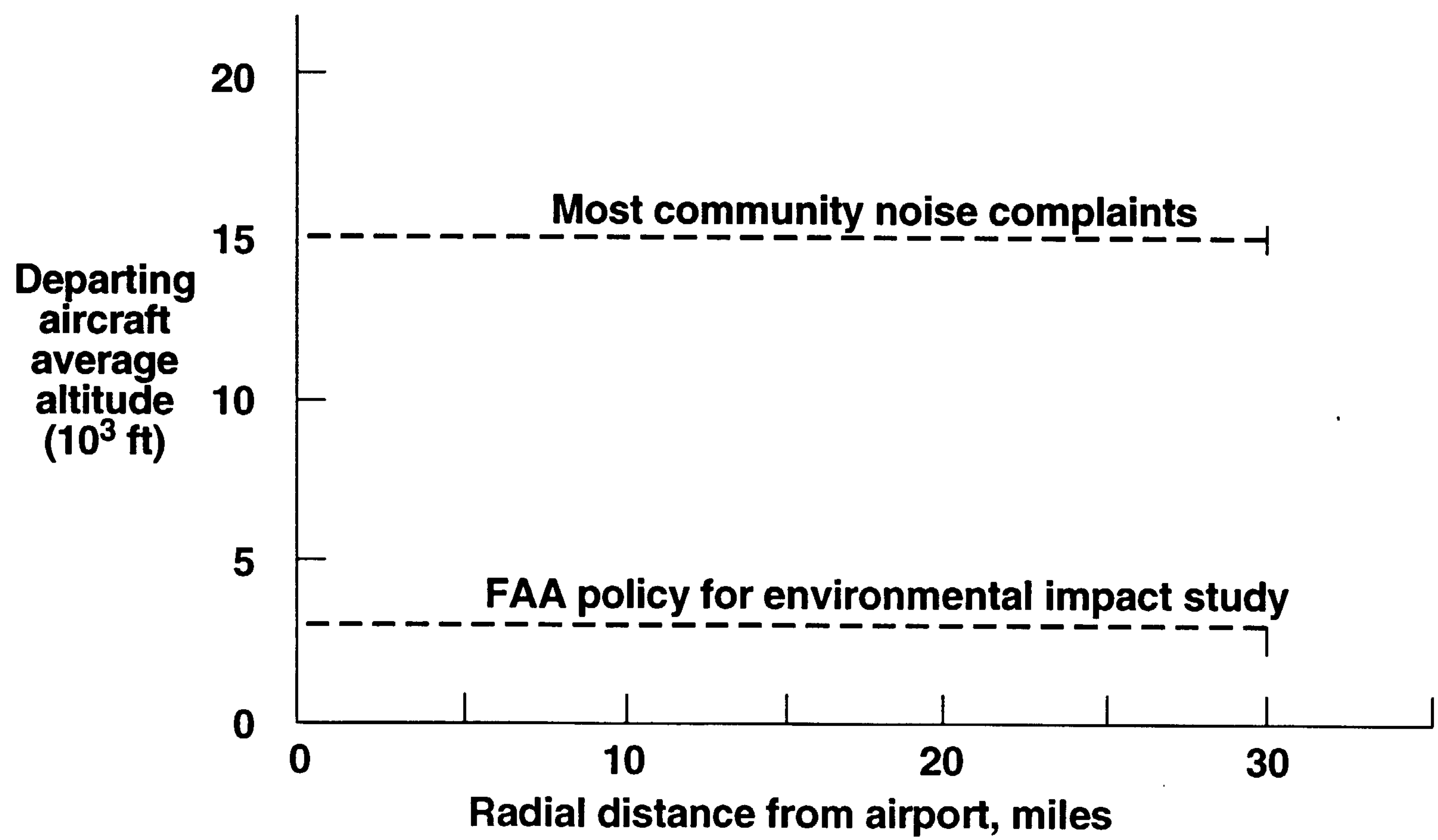

Figure 14. Environmental impact of aircraft route changes and noise abatement.

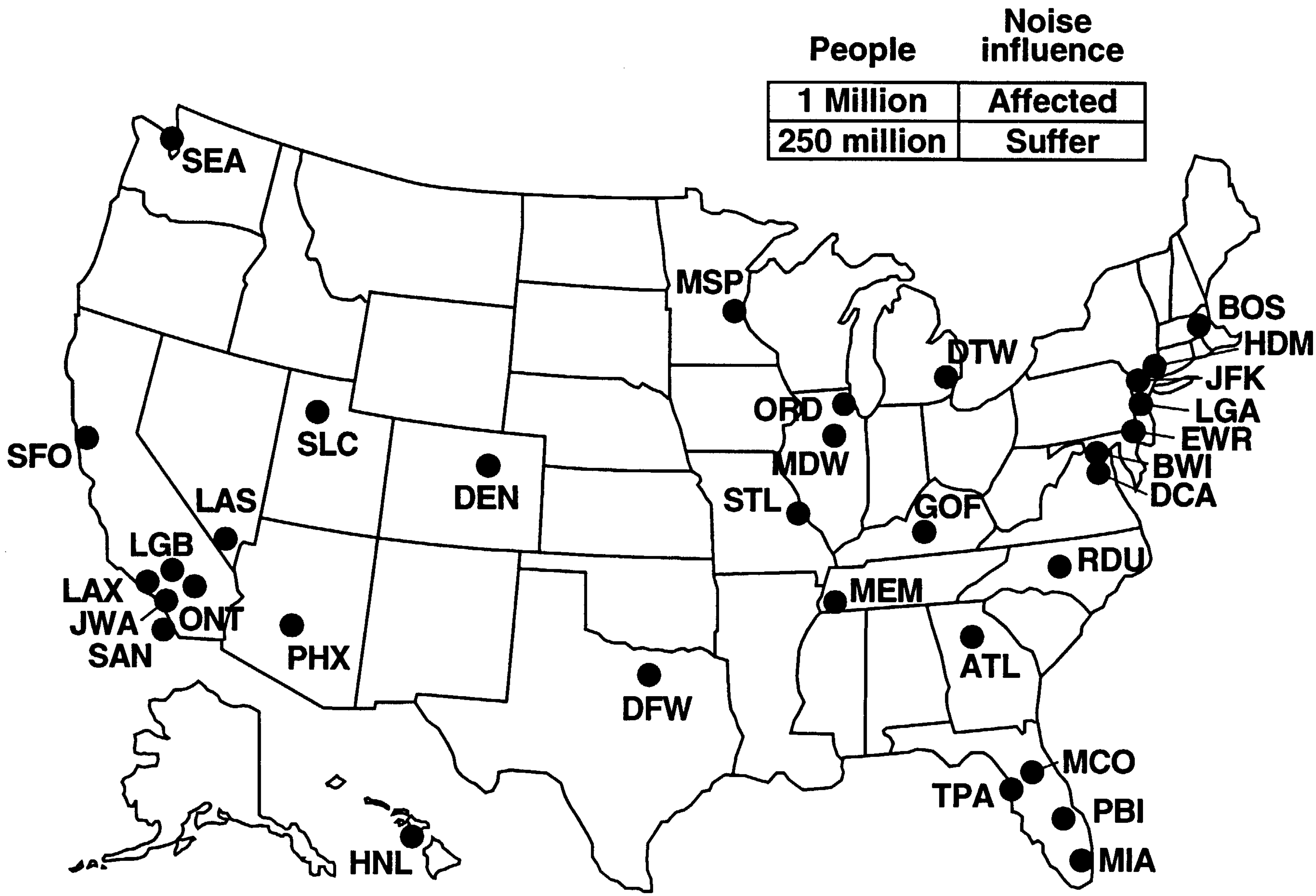

Figure 15. Noise impacted airports of most concern in 1990.

Figure 16. Major U.S. airports with nighttime curfews.

- Phase-out option - Reduce or modify Stage 2 aircraft fleet 25% by end of 1994; 50% by end of 1996; 75% by end of 1998; 100% by end of 2000

- Phase-in option - Total fleet is 55% Stage 3 by end 1994; 65% by end of 1996; 75% by end 1998; 100% by end 2000

- Waivers or exemptions permitted if fleets are 85% compliant by 7/1/99 with planned phase-out by end of 2003

- Rules apply to all U.S. and foreign carriers except for Concorde aircraft

Ref. Aviation Week, 9/30/91 and Interavia, 5/91

Figure 17. FAA aircraft noise rules and airline compliance requirements.

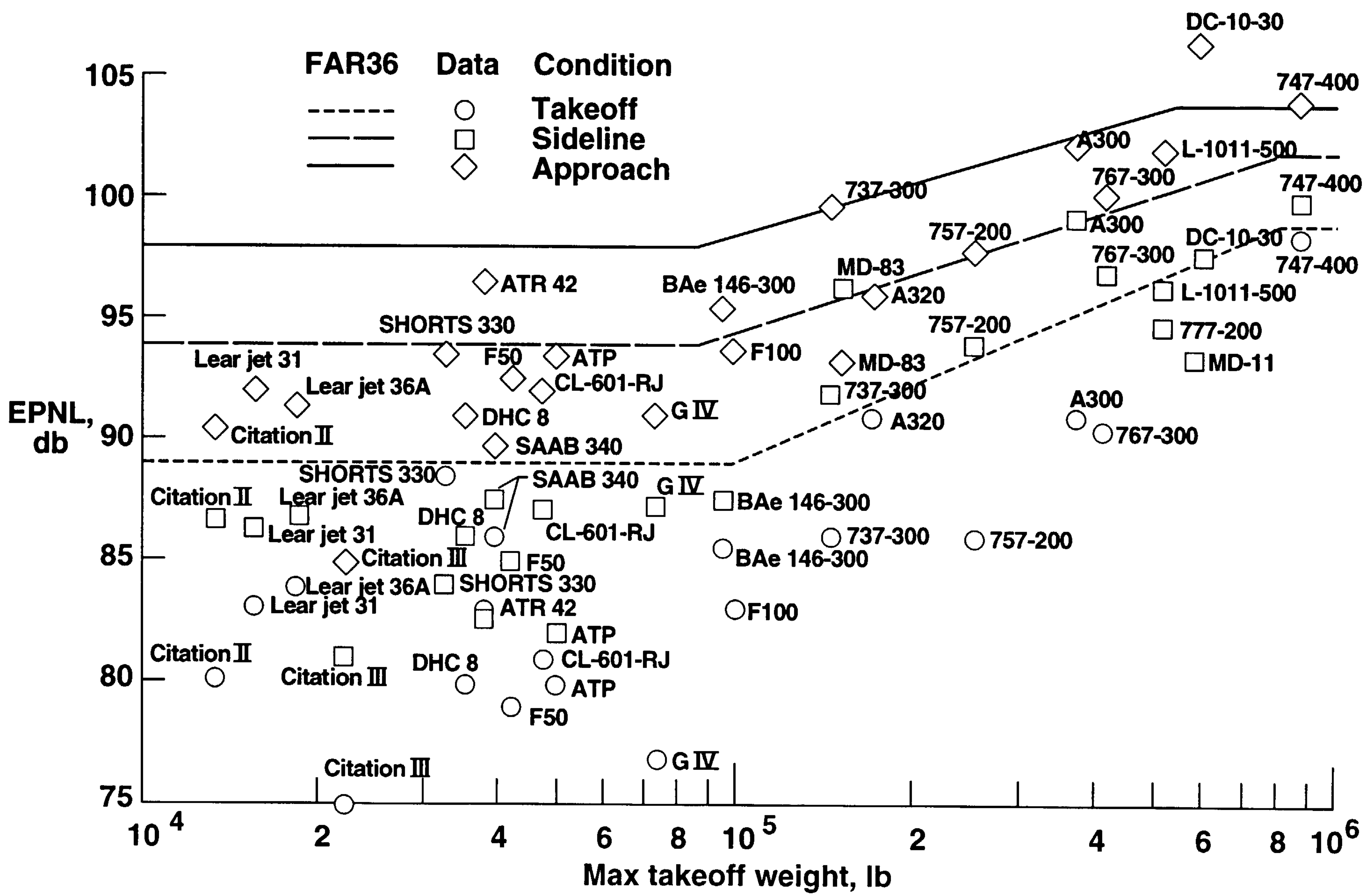

Figure 18. Comparison of maximum allowable noise level variation with takeoff weight for far 36 stage 3 compliance.

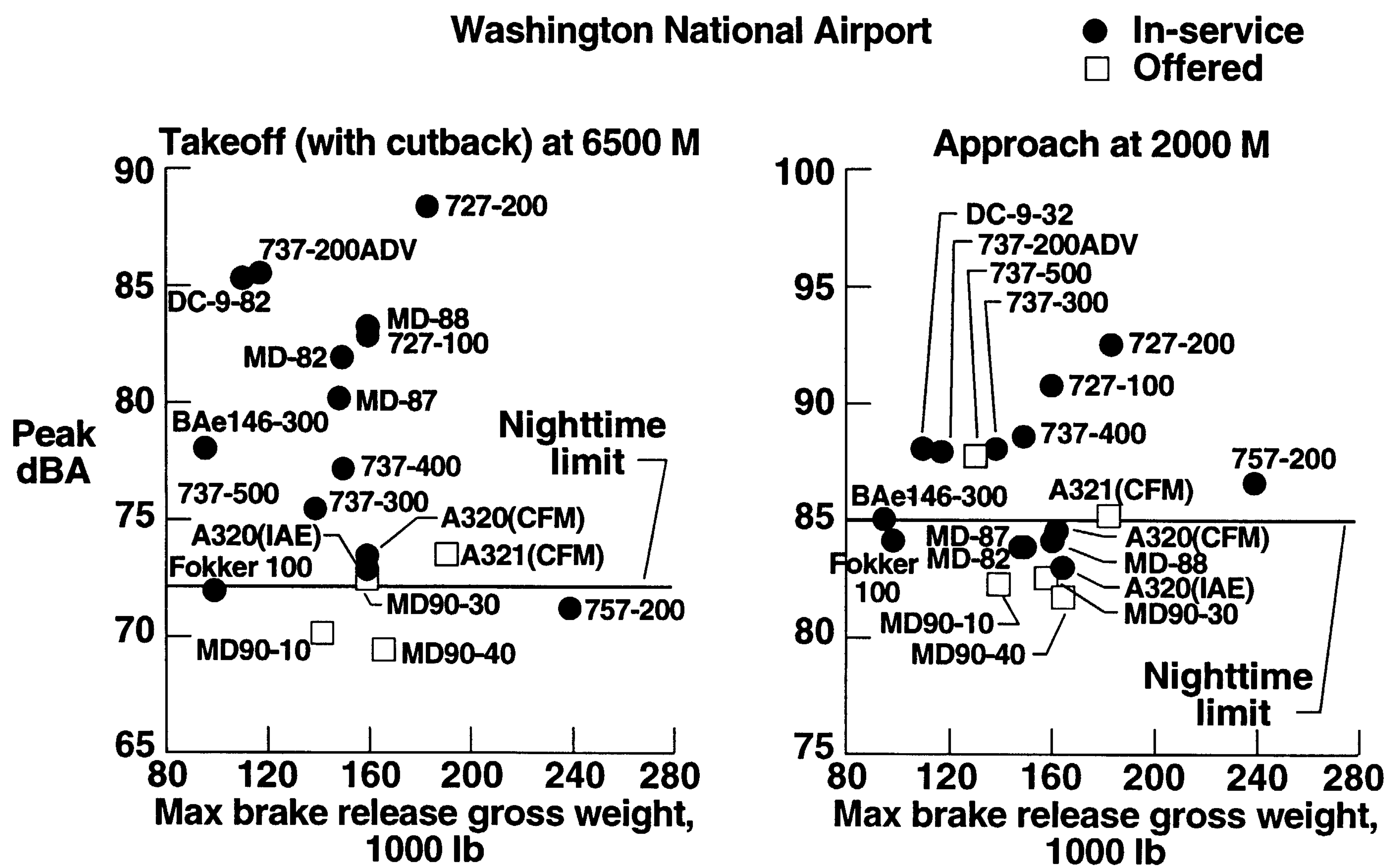

Figure 19. Example of airport access noise level restrictions for nighttime operations compared with several aircraft.

	Stage 2 Narrow-body fleet 1990	Required retirement by 1994 (25%)	Stage 2 lease expirations 1991-1994	Firm narrow-body orders 1991-1994
American	174	44	43	160
America West	33	8	11	30
Continental	169	42	31	70
Delta	224	56	5	79
Northwest	223	56	27	64
Pan American	67	17	26	0
Southwest	46	11	8	41
TWA	113	28	46	0
United	202	50	0	180
USAir	220	55	22	68
Total majors	1,471 *	367	219	692

* ~ 45% of total fleet

Source: Avmark, as of December 1990

Figure 20. Effect of noise proposal on narrow-body fleet by 1994.

Stage 2 fleet ≈ 2,600 transports; 50% of U.S. total

SOURCE	EST. COST ($B)	ASSUMPTIONS
FAA	2.7	Incremental cost of early retirement less savings of fuel-efficient stage 3 aircraft
American Airlines	3.1	
AVMARK Consultants	59.6	Full replacement value
Government Accounting Office	2 to 5	Depending on wheather full replacement, reengining or hush kits
Air Transport Association	100	
S.K. Skinner (DOT)	0.8 to 4	
Sen, Wendall Ford (D-KY)	25	

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Figure 21. Industry-wide cost estimates for stage 2 banned aircraft.

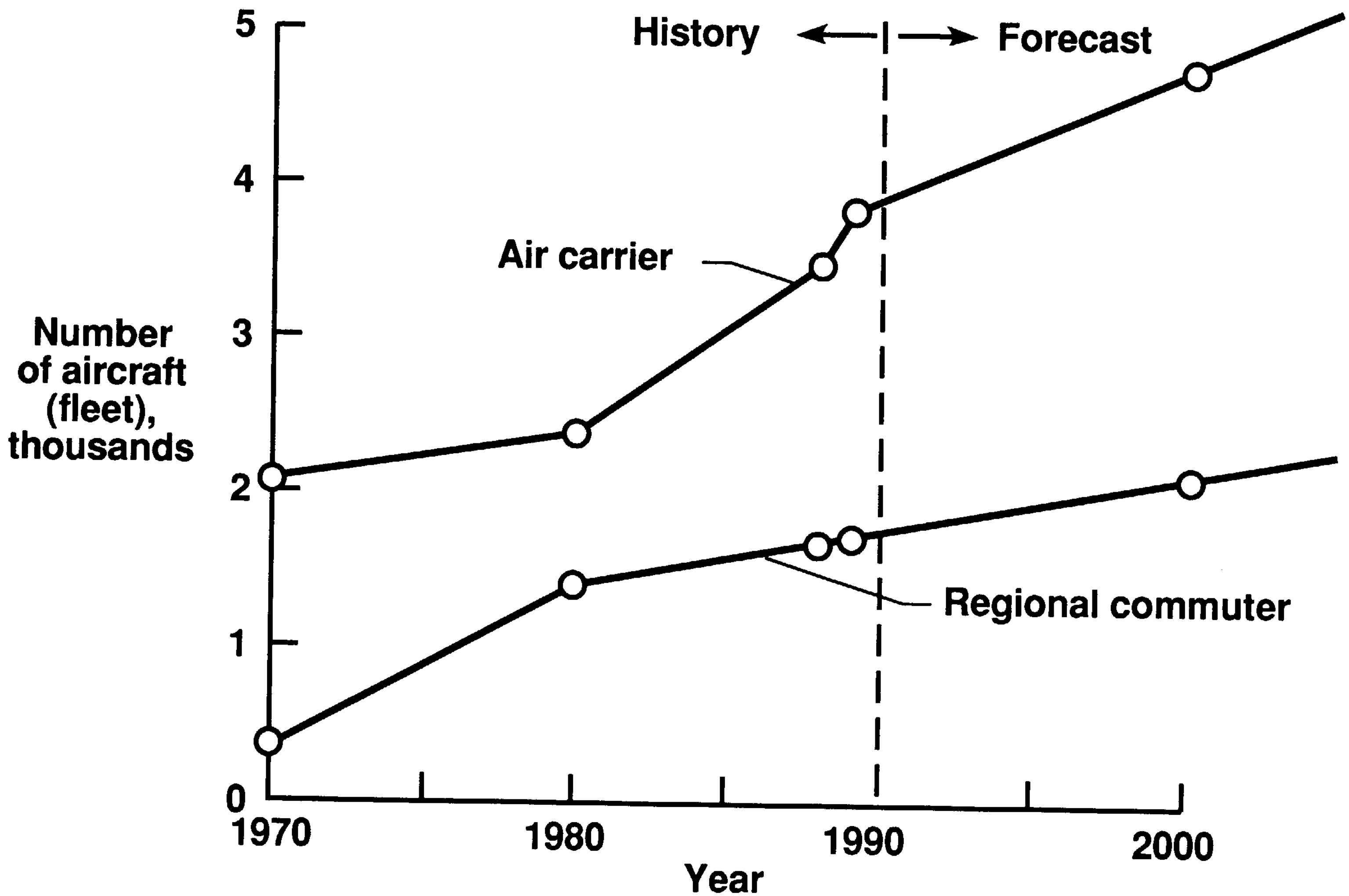


Figure 22. History and forcast of U.S. airline aircraft requirements.

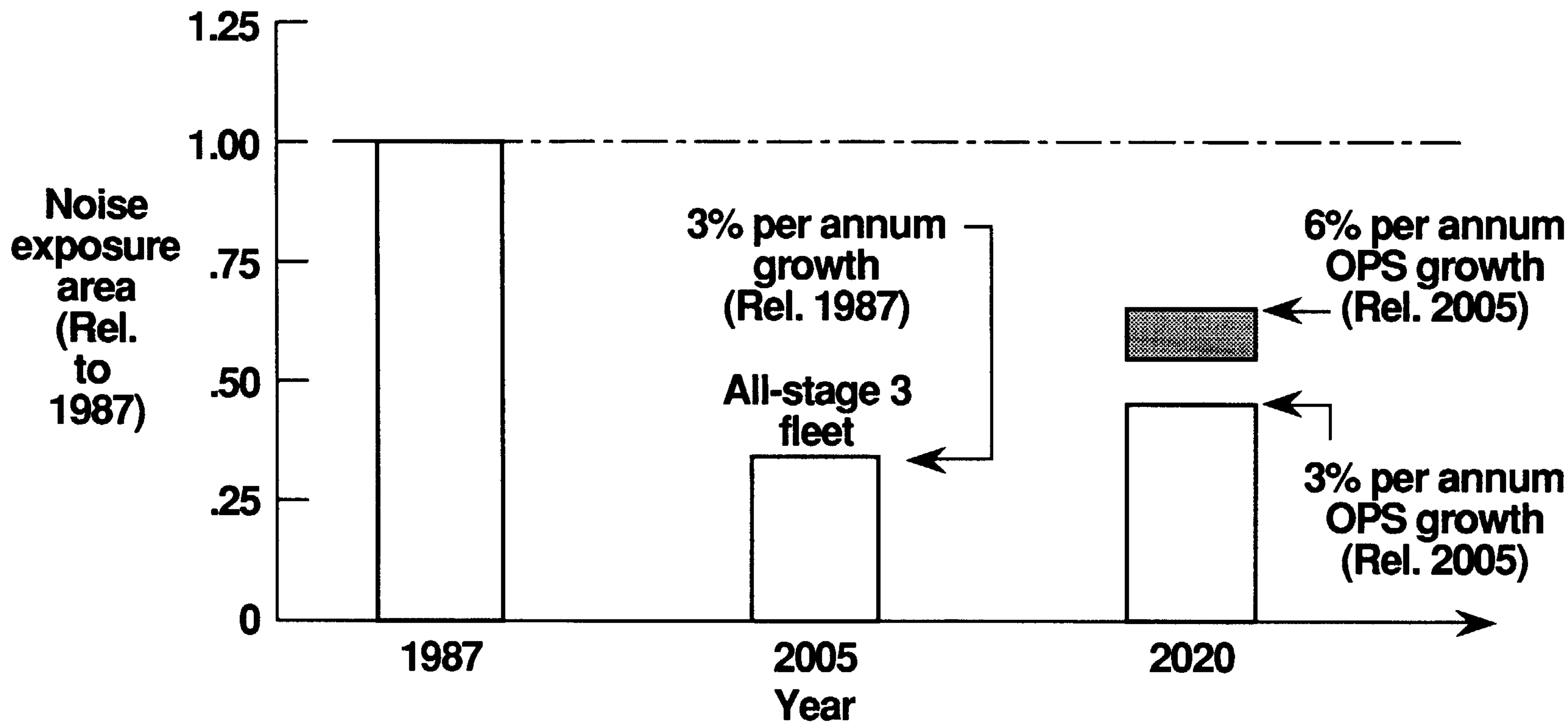
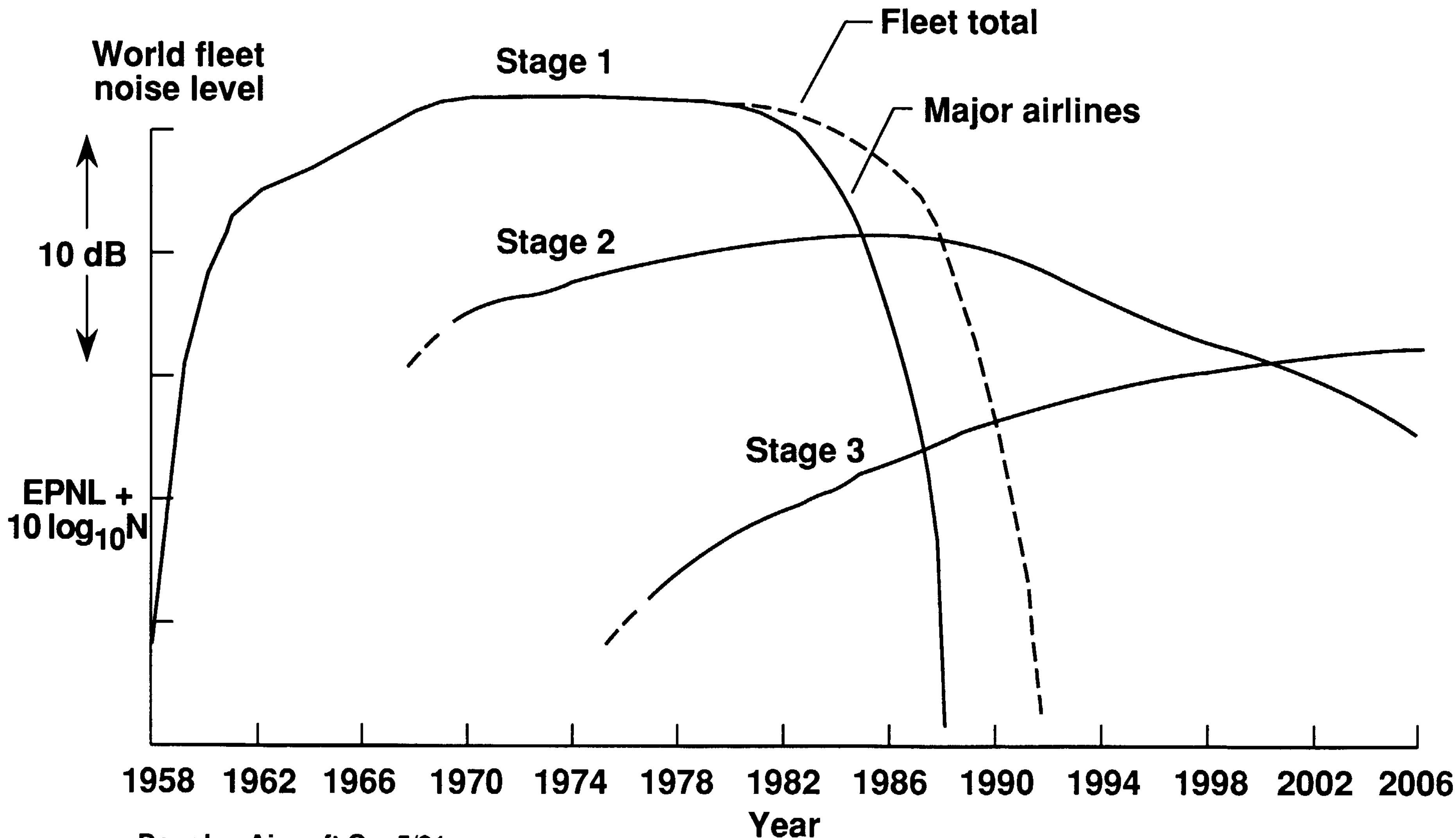


Figure 23. Noise climate projections for an all-stage 3 aircraft fleet.



Douglas Aircraft Co. 5/91
ICCAIA Study

Figure 24. Past and projected noise exposure trends.

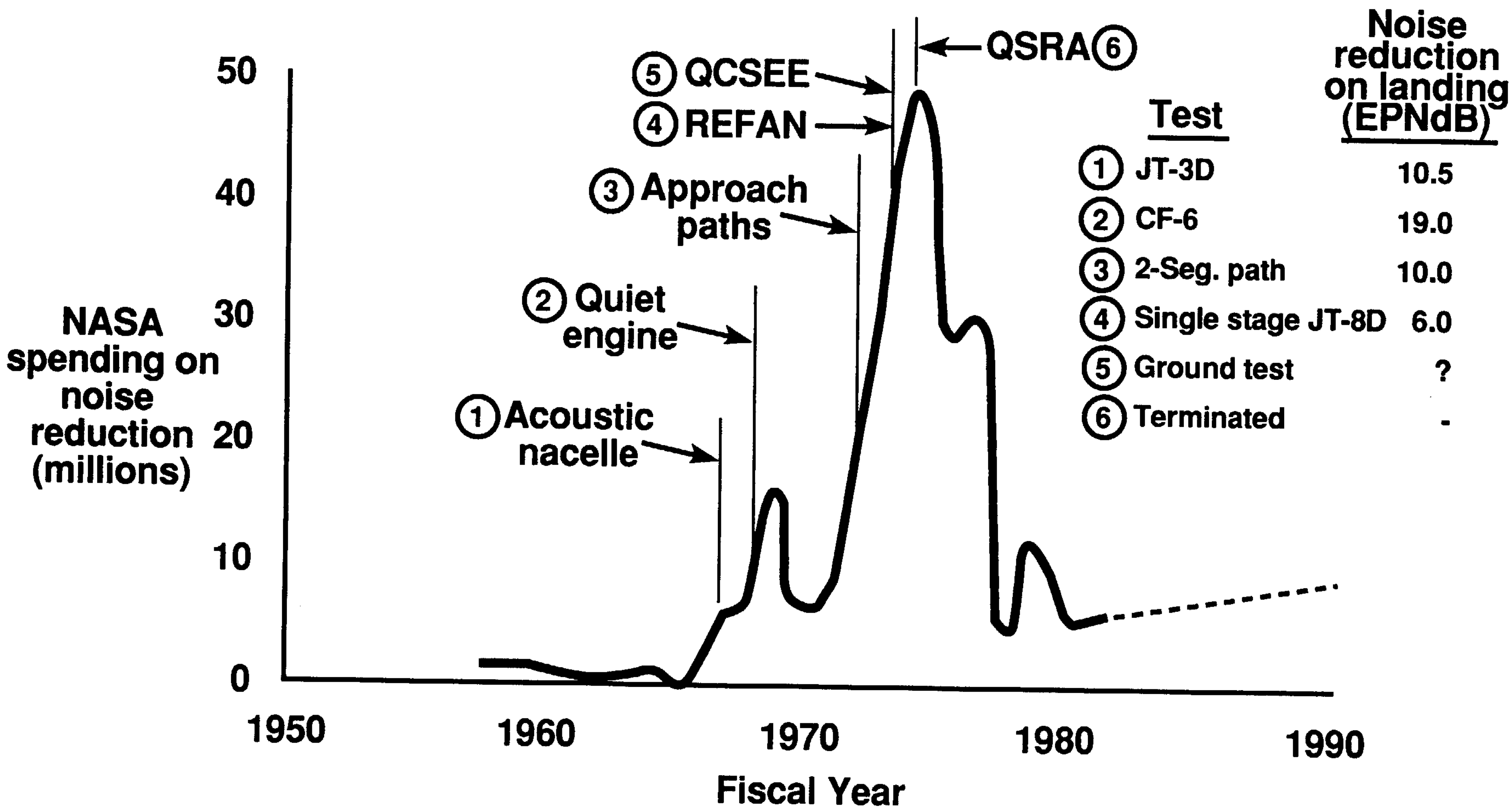


Figure 25. Previous NASA program spending on aircraft noise reduction.

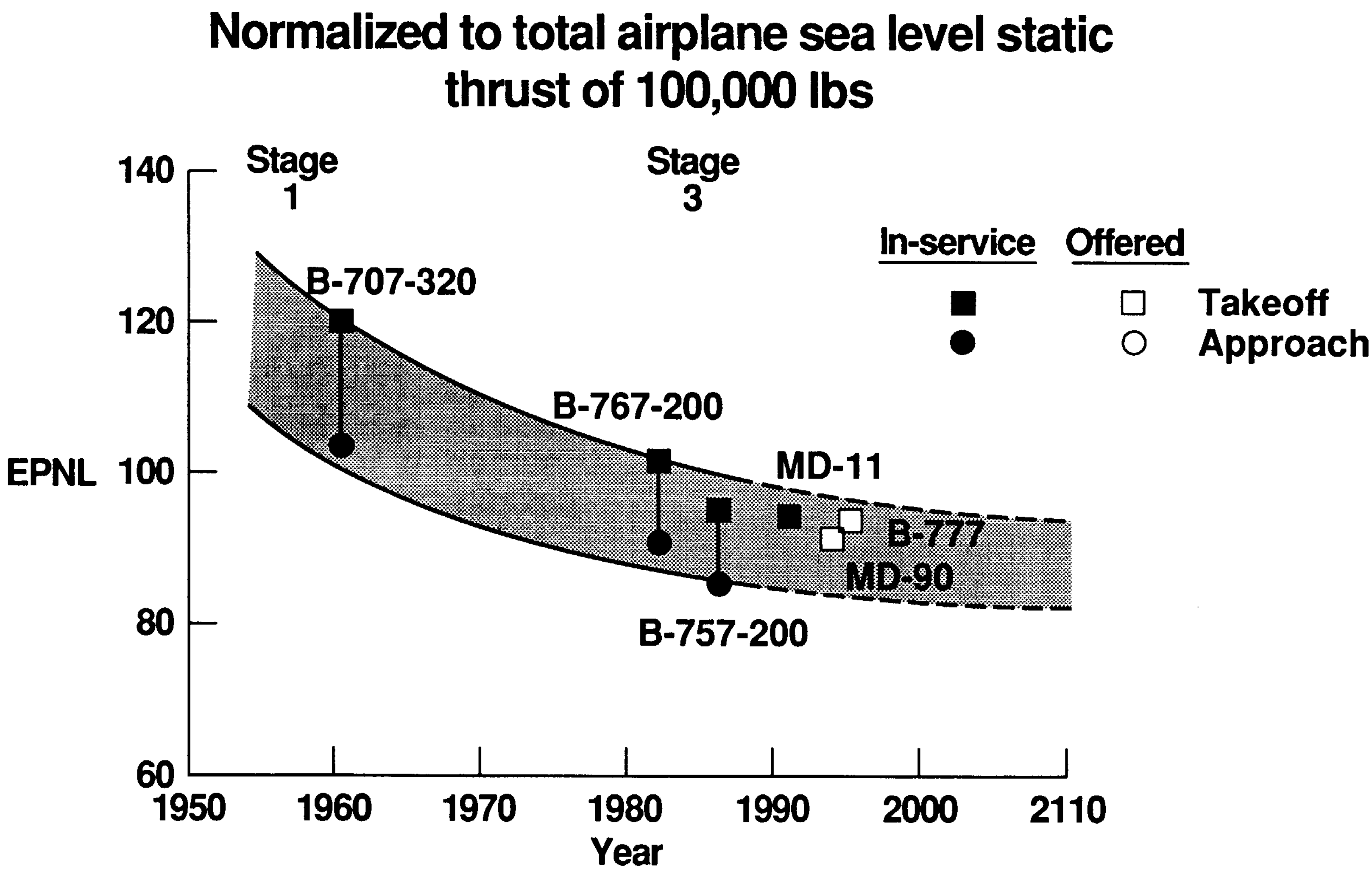


Figure 26. Progress and projection in aircraft noise reduction.

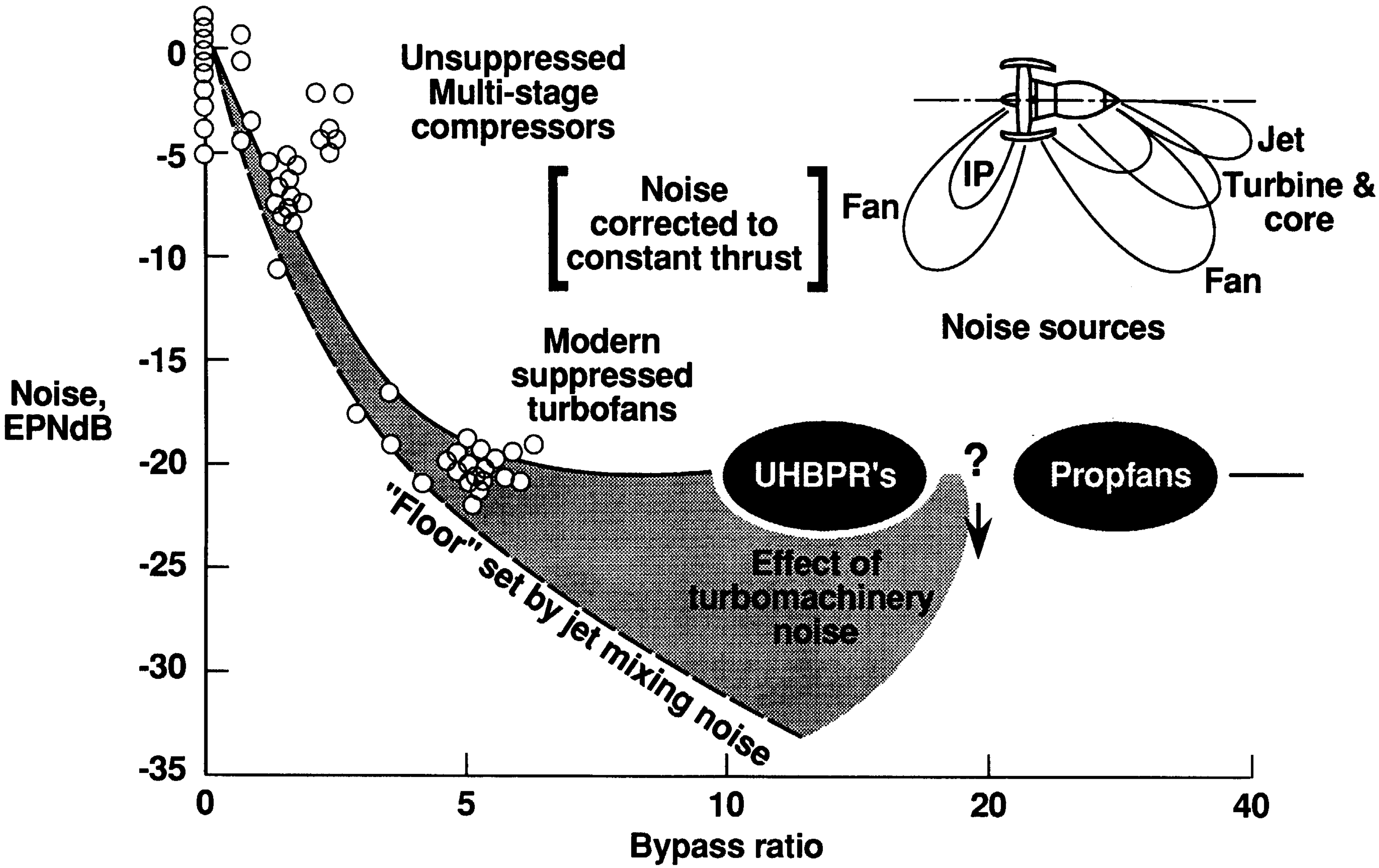


Figure 27. Variation in engine noise source reduction with bypass ratio.

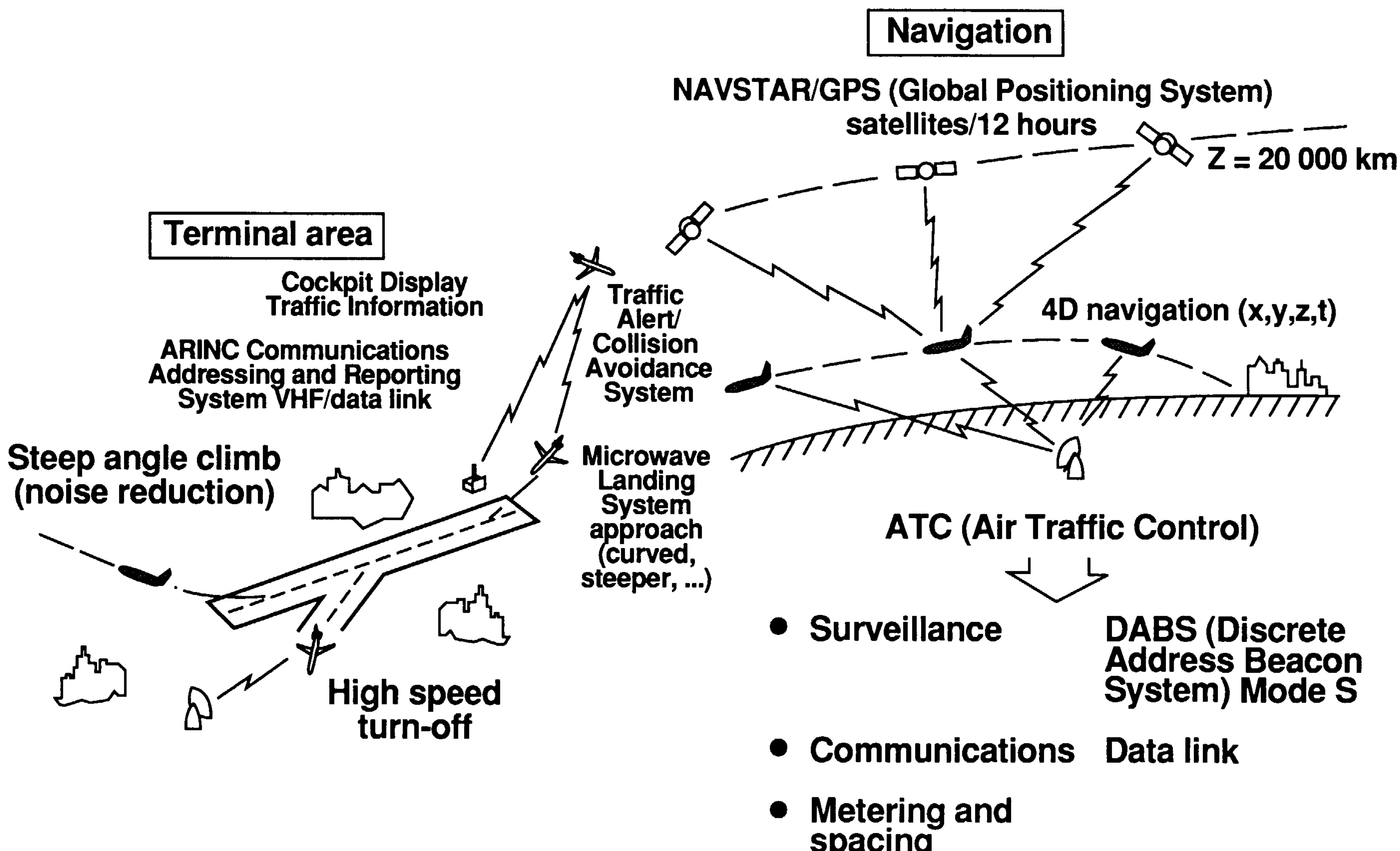


Figure 28. Future ATC and FMS improvements for en route and terminal area.

1. **Aircraft Navigation Technology -**
   the means of providing high quality aircraft position information the aircraft flight control system and crew

2. **Aircraft Guidance -**
   the means of ensuring the conformance of aircraft to complex trajectories (2, 3, and 4-D) as defined by ATC controller and pilot

3. **Aircraft Surveillance Technology -**
   the means of providing high quality traffic information to ATC ground facilities and aircraft consisting of:
   1. aircraft state (position, position rates, heading, etc.)
   2. meteorological information on turbulence, wake vortex, precipitation, microbursts, winds, and temperatures

4. **Air-Ground Communication Technology -**
   the capability to exchange information between aircraft and ground in voice, digital, and pictorial for

5. **Human Centered Automation Technology -**
   the means of providing the interaction between real-time human operators and their automated decision support systems

Figure 29. Definitions of technologies for separation reduction in ATC.

1986

1st landing aircraft \ 2nd landing aircraft	(H)	(L)	(S)
(H)	4 (N miles)	5	6
(L)	3	3	4
(S)	3	3	3

1991

1st landing aircraft \ 2nd landing aircraft	(H)	(L)	(S)
(H)	4	5	6
(L)	3	2.5	4
(S)	3	3	2.5

(H) Heavy - TOW > 300,000 lbs
(L) Large - 12,500 < TOW < 300,000 lbs
(S) Small - TOW < 12,500 lbs

Figure 30. Aircraft separation criteria on final approach.

No. 2 aircraft \ No. 1 aircraft		Takeoff		Landing	
		Heavy	Other	Heavy	Other
Takeoff	Heavy	125*	72	80	50
	Other	125*	72	80	50
Landing	Heavy	100	100	120	100
	Other	100	100	120	100

* FAA spec

Figure 31. Average separation times (seconds) for aircraft takeoff and landings with other traffic mix of equal large and small aircraft.

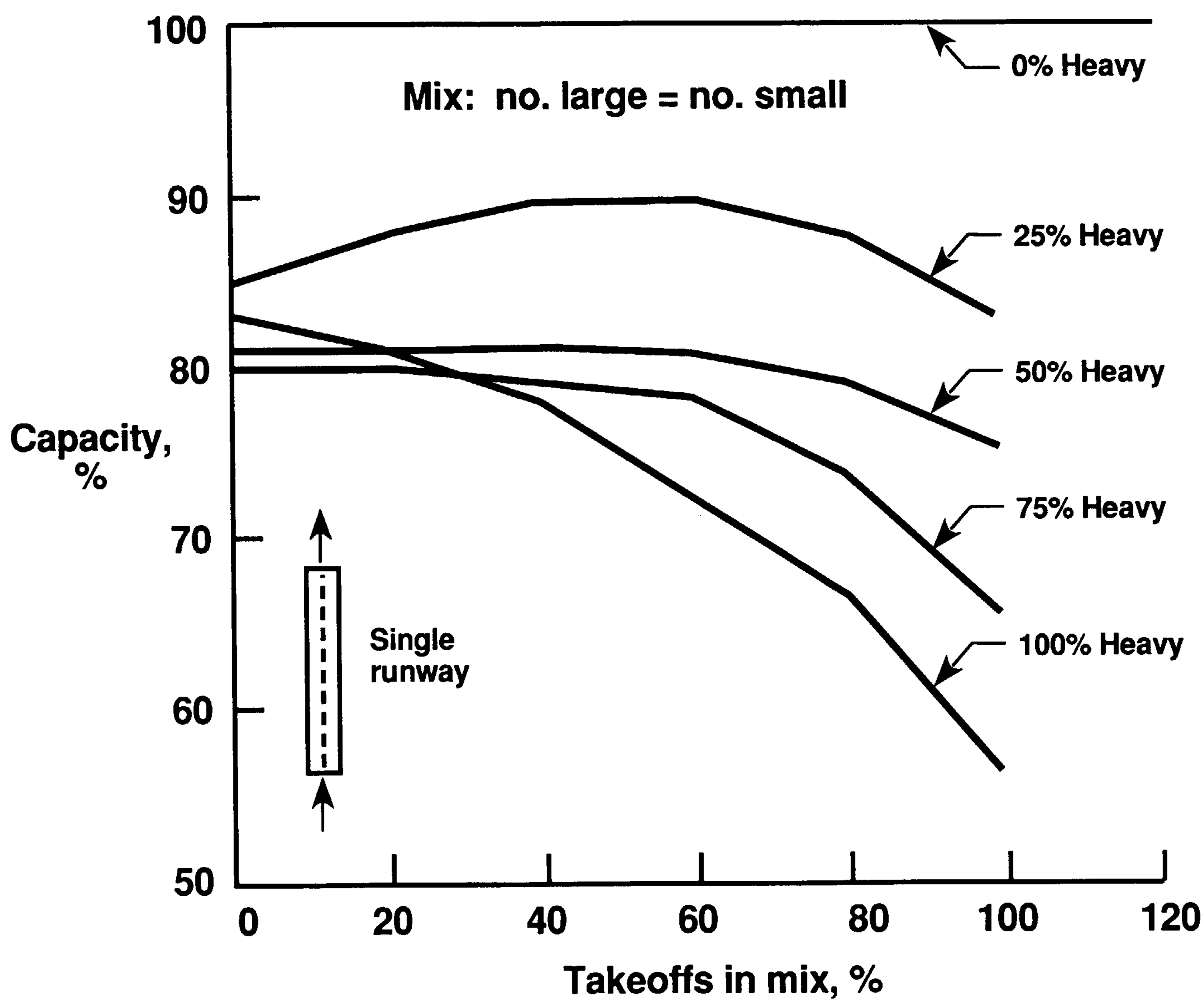


Figure 32. Effect of heavy jet aircraft mix and takeoff-landing rates on capacity.

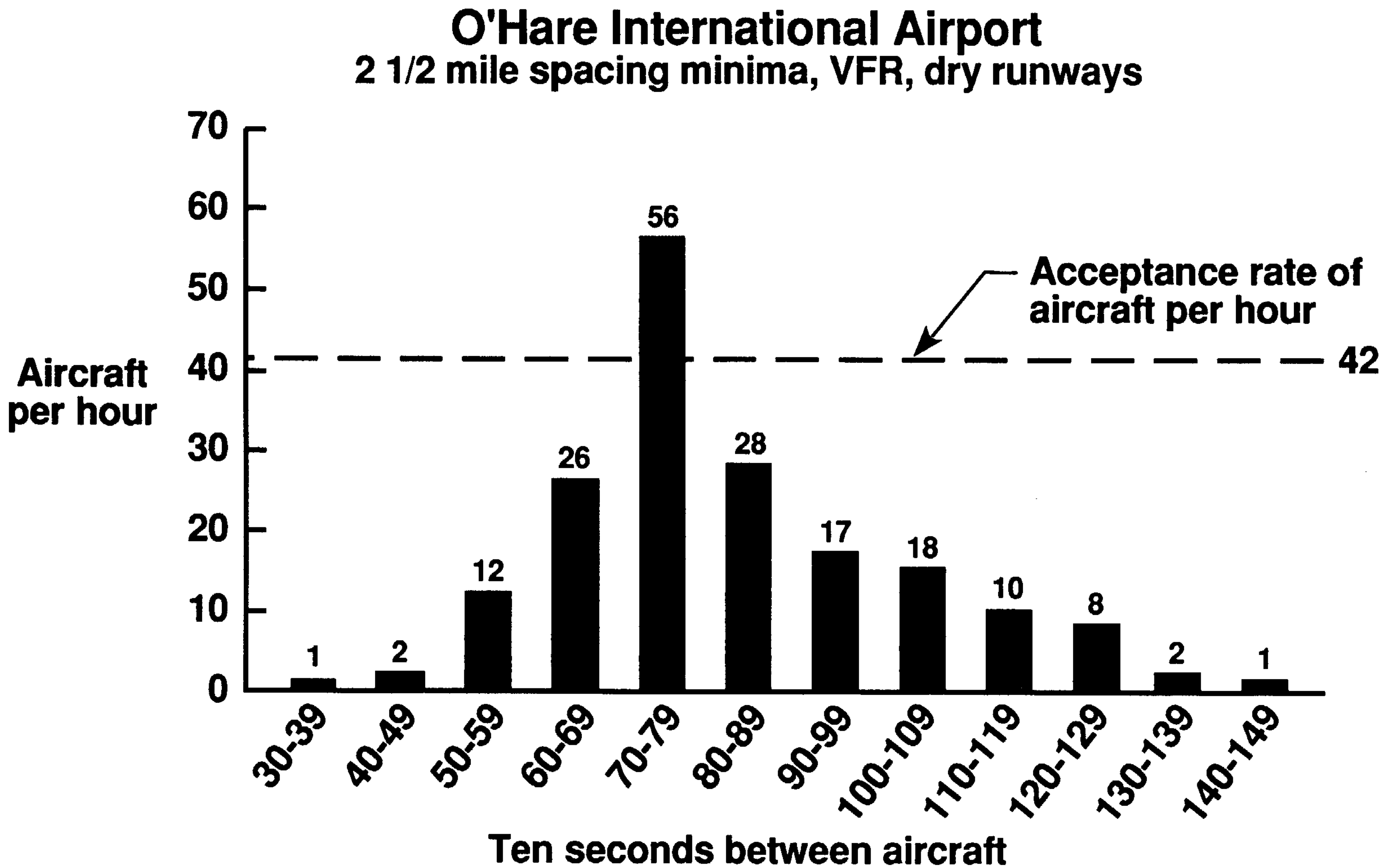


Figure 33. Example of observed aircraft spacing and frequency distribution per hour.

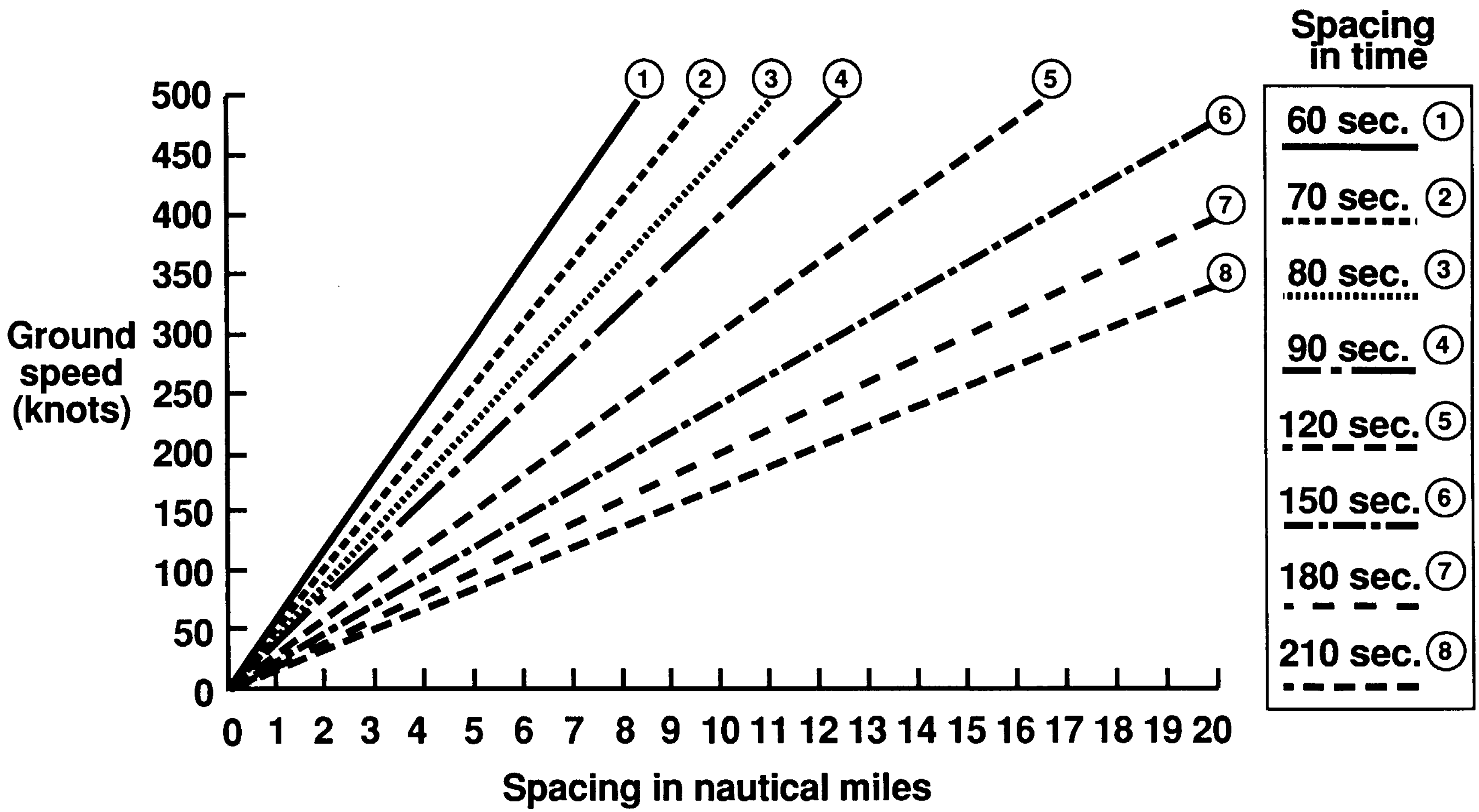


Figure 34. Typical chart for aircraft spacing distribution and arrival rates.

Aircraft classifications

Model class	Aircraft type	Wake vortex class	Final approach speed
A	Small aircraft	I Small	100 Kts
B	Large prop	II Large	110 Kts
C	Large jet	III Large	130 Kts
D	Heavy jet	III Heavy	140 Kts

Parameters used in today's VFR OPS

Parameter	Aircraft class			
	A	B	C	D
Arrival separations, nmi				
Behind heavies	4.5	3.6	3.6	2.7
Behind all others	2.7 *	1.9	1.9	1.9
Departure separations, sec.				
Behind heavies (D)	120	120	120	90
Behind large (B, C)	50	60	60	60
Behind small (A)	35	45	45	50
Arrival ROT, sec.				
Mean	40	40	45	50
Standard deviation	10	10	10	10
Departure ROT, sec.				
Mean	35	35	40	40
Standard deviation	6	6	6	6
IAT variability, sec.	18	18	18	18
Length of final approach, nmi	3	3	5	5

*1.9 for class A behind class A

(a) Today's VFR operations.

Figure 35. Parameters used by the MITRE Corporation to model airfield capacity.

Aircraft classifications

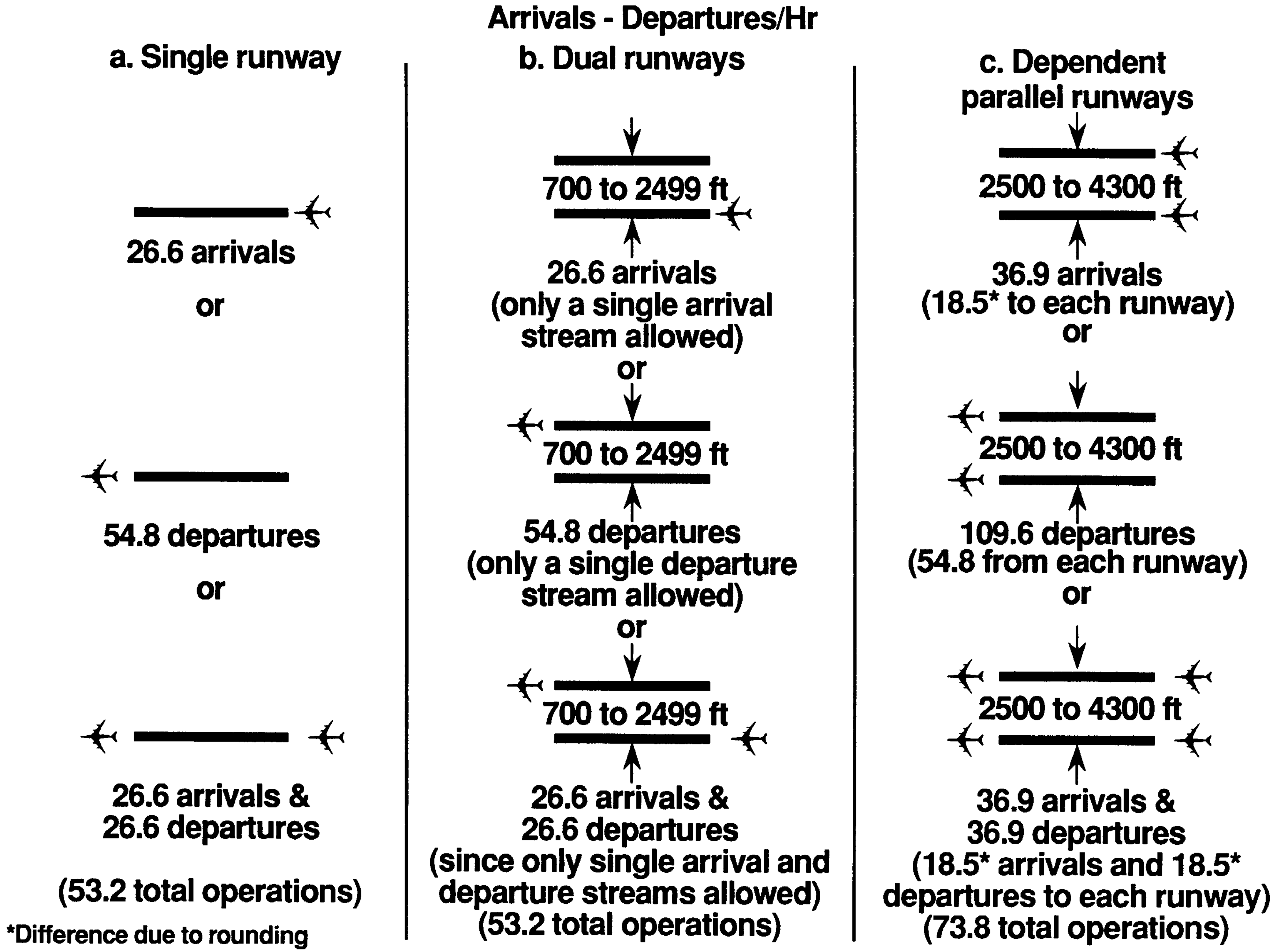
Model class	Aircraft type	Wake vortex class	Final approach speed
A	Small aircraft	I Small	100 Kts
B	Large prop	II Large	110 Kts
C	Large jet	III Large	130 Kts
D	Heavy jet	III Heavy	140 Kts

Parameters used in today's IFR OPS

Parameter	Aircraft class			
	A	B	C	D
Arrival separations, nmi				
Behind heavies	6.0 *	5.0	5.0	4.0
Behind all others	4.0	3.0	3.0	3.0
Departure separations, sec.				
Behind heavies (D)	120	120	120	90
Behind all others (A, B, C)	60	60	60	60
Arrival ROT, sec.				
Mean	40	40	45	50
Standard deviation	10	10	10	10
Departure ROT, sec.				
Mean	35	35	40	40
Standard deviation	6	6	6	6
IAT variability, sec.	18	18	18	18
Length of final approach, nmi	7	7	7	7

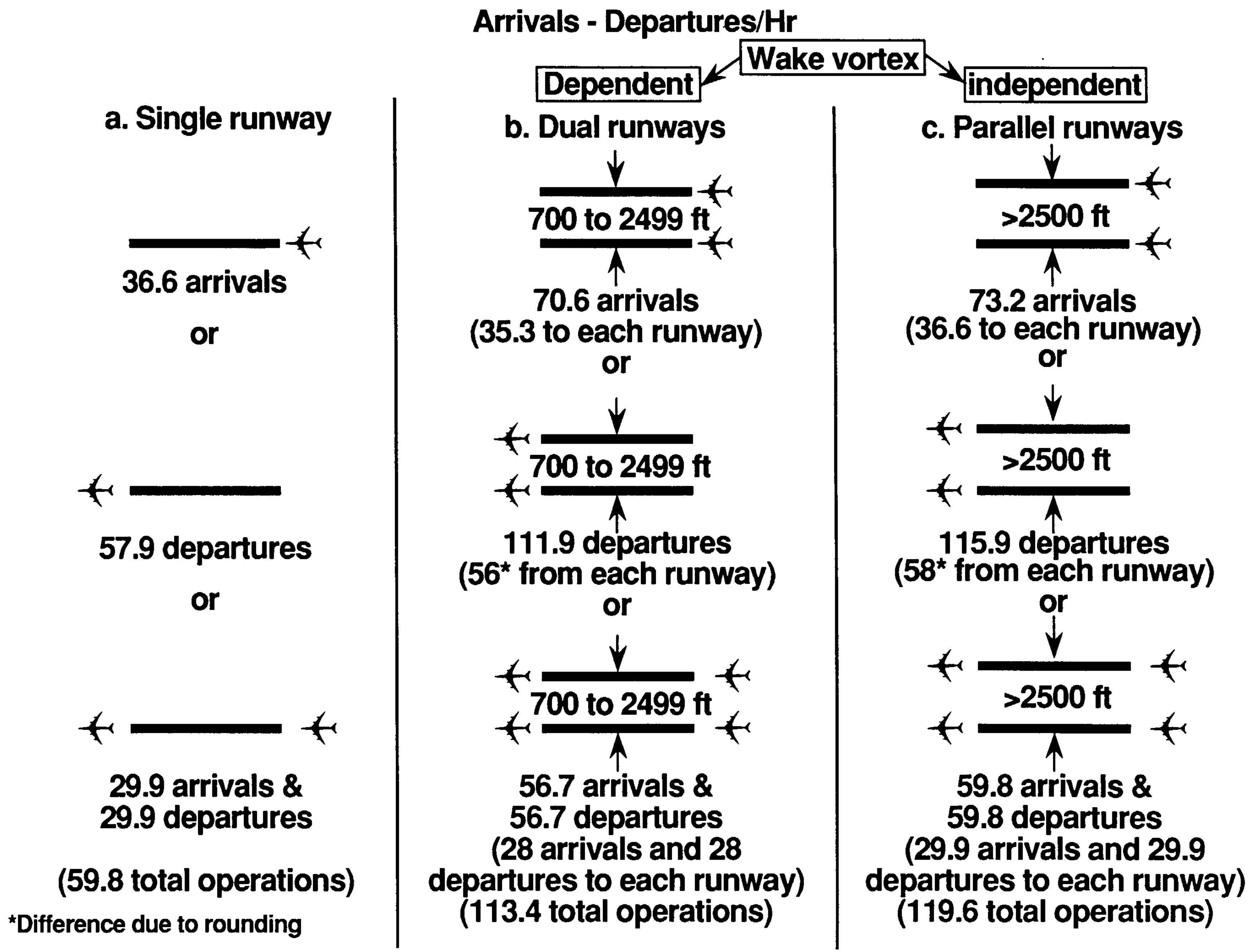
*3.0 for class A behind class A

(b) Today's IFR operations.
Figure 35 Concluded



(a) Today's VFR operations.

Figure 36. Capacity results calculated by the MITRE Corporation for Today's operations.



(b) Today's IFR operations.
Figure 36 Concluded

Arrivals ONLY

Parameter	Reduction From	Reduction To	Percentage increase in VFR capacity
IAT variability	18 sec.	9 sec.	17-18%
Interarrival separations (observed)	1.9-4.5 nmi	1.7-4.0 nmi	7%
Common final	3-5 nmi	2-3 nmi	2-3%
Arrival ROT mean	40-50 sec.	30-40 sec.	0%
Arrival ROT variability	10 sec.	5 sec.	0%

50% Arrivals, 50% Departures

Parameter	Reduction From	Reduction To	Percentage increase in VFR capacity
Arrival ROT mean	40-50 sec.	30-40 sec.	8-9%
Departure ROT mean	35-40 sec.	25-30 sec.	4%
Departure ROT variability	6 sec.	4 sec.	3%
Departure separations	50-60 sec. (120 sec./heavies)	40-50 sec. (100 sec./heavies)	3%
IAT variability	18 sec.	9 sec.	<1%
Arrival ROT variability	10 sec.	5 sec.	<1%
Interarrival separations	1.9-4.5 nmi	1.7-4.0 nmi	0%
Common final	3-5 nmi	2-3 nmi	0%

Departures ONLY

Parameter	Reduction From	Reduction To	Percentage increase in VFR capacity
Departure separations	50-60 sec. (120 sec./heavies)	40-50 sec. (100 sec./heavies)	18%
Departure ROT mean	35-40 sec.	25-30 sec.	0%
Departure ROT variability	6 sec.	4 sec.	0%

(a) Today's VFR capacity.

Figure 37. Calculated increases in capacity from parameters reductions in Figures 35 and 36

Arrivals ONLY

Parameter		Reduction From	Reduction To	Percentage increase in IFR capacity
Interarrival separations	Diag. [1]	2 nmi	1 nmi	25%
	Long. [2]	3-6 nmi	2 1/2-5 nmi	15%
IAT variability		18 sec.	9 sec.	12-16%
Common final		7 nmi	5 nmi	2-3%
Arrival ROT	mean	40-50 sec.	30-40 sec.	0%
	variability	10 sec.	5 sec.	0%

50% Arrivals, 50% Departures

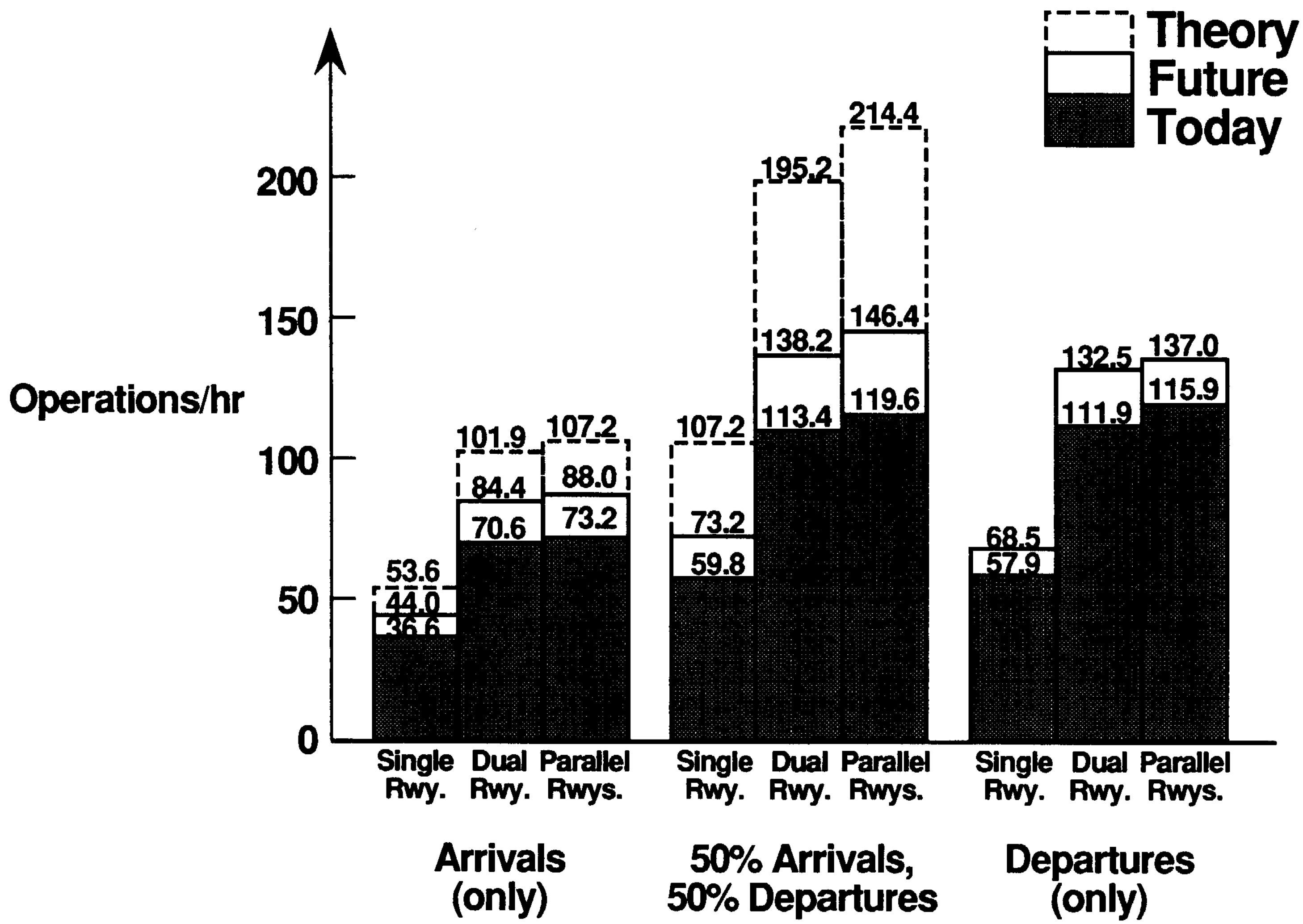
Parameter		Reduction From	Reduction To	Percentage increase in IFR capacity
Interarrival separations	Diag. [1]	2 nmi	1 nmi	25%
	Long. [2]	3-6 nmi	2 1/2-5 nmi	15%[3]
IAT variability		18 sec.	9 sec.	12-16%[3]
Common final		7 nmi	5 nmi	2-3%
Arrival ROT	mean	40-50 sec.	30-40 sec.	0%
	variability	10 sec.	5 sec.	0%
Departure ROT	mean	35-40 sec.	25-30 sec.	0%
	variability	6 sec.	4 sec.	0%

Departures ONLY

Parameter		Reduction From	Reduction To	Percentage increase in IFR capacity
Departure separations		50-60 sec. (120 sec./heavies)	40-50 sec. (100 sec./heavies)	20%
Departure ROT	mean	35-40 sec.	25-30 sec.	0%
	variability	6 sec.	4 sec.	0%

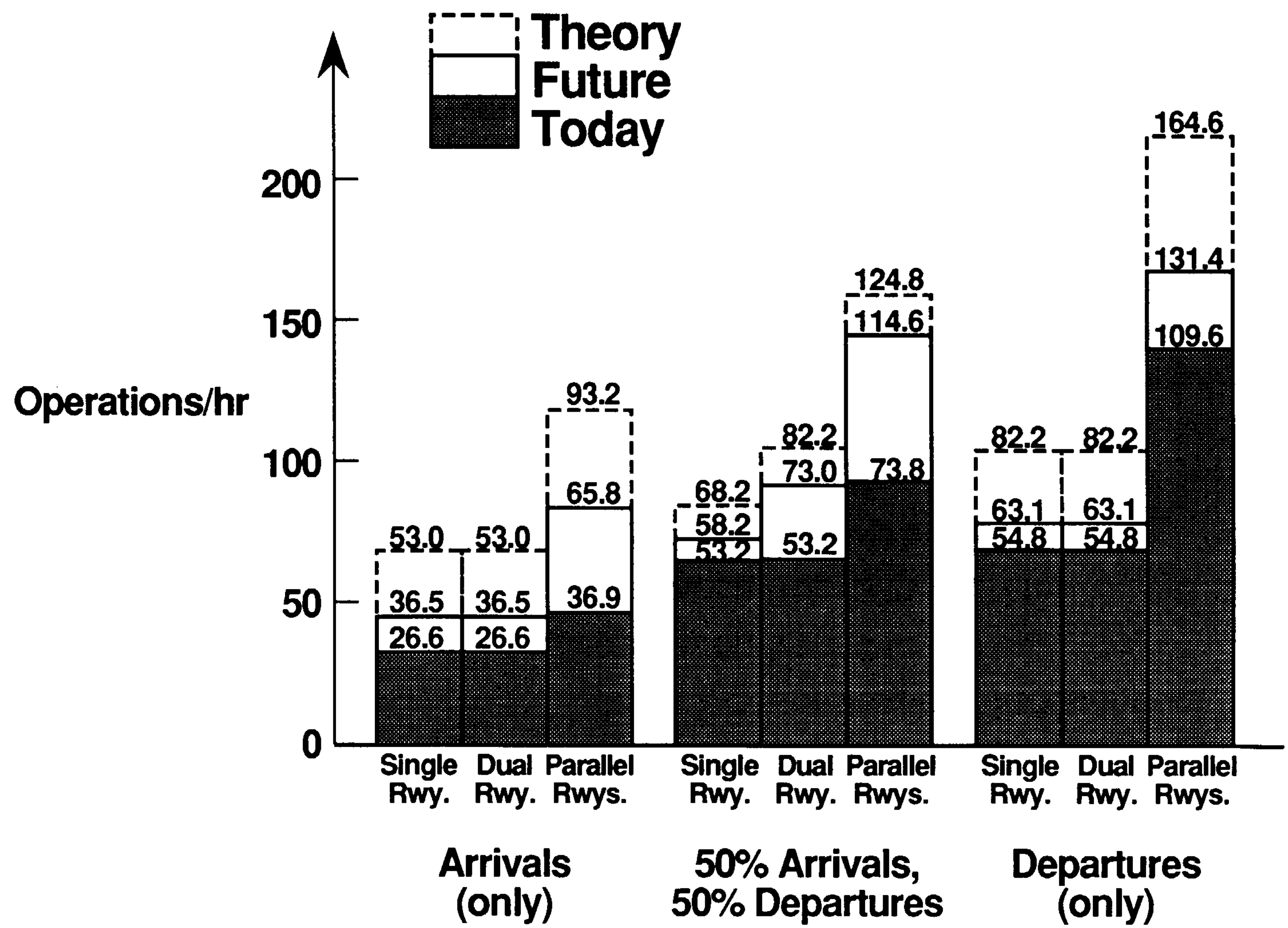
1 For dependent parallels only.
2 For single & dual runways only.
3 Capacity increase limited to 3-4% for single runways due to ROT limitations.

(b) Today's IFR capacity.
Figure 37 Concluded



(a) VFR capacity

Figure 38. Calculated theoretical and "realistic" upper bound capacity increases.



(b) IFR capacity
Figure 38 Concluded

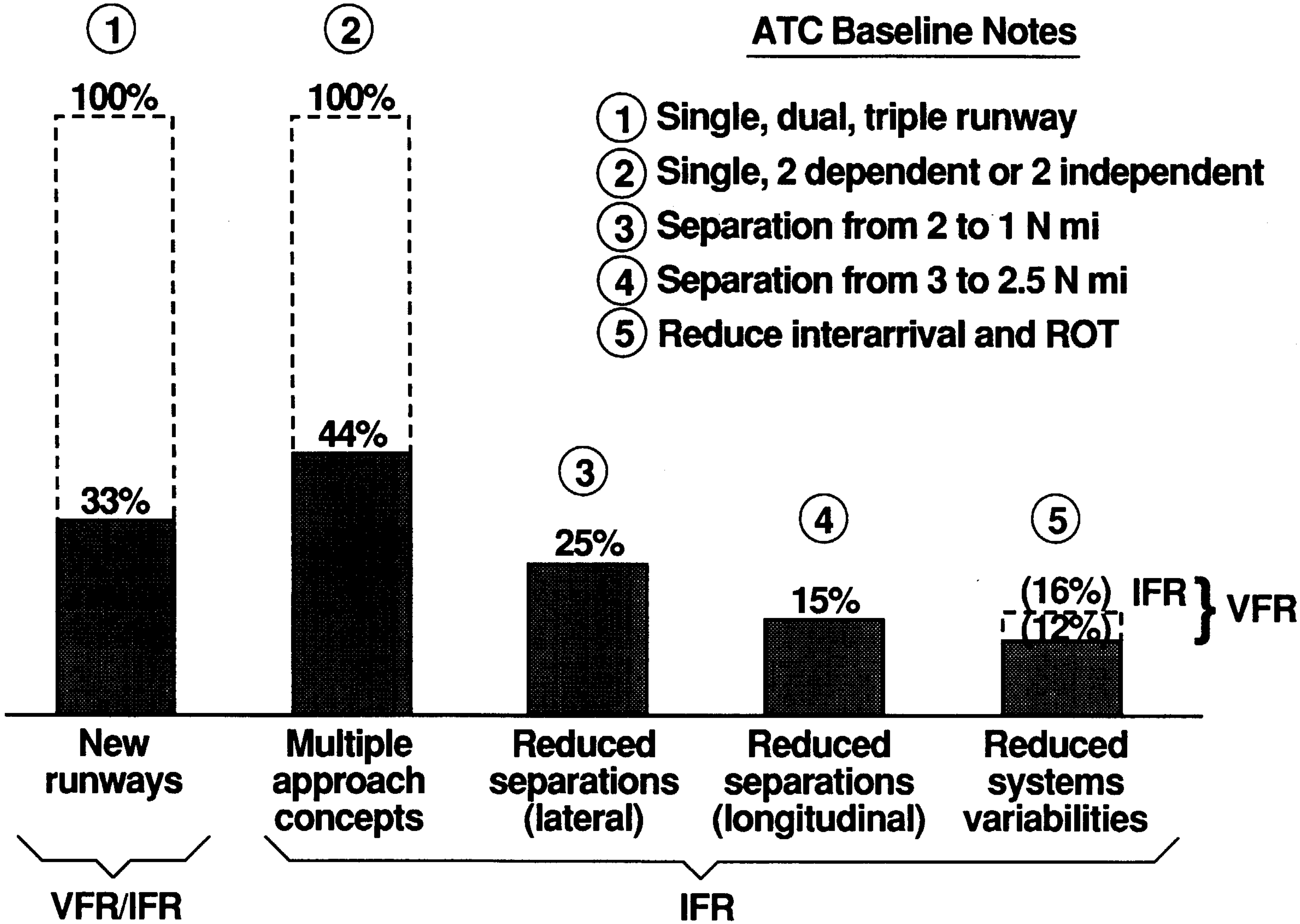


Figure 39. Summarized estimates of potential airport-airspace capacity improvements.

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A study was conducted with the primary objective of determining the impact of technology on capacity improvements in the U.S. air transportation system and, consequently, to assess the areas where NASA's expertise and technical contributions would be the most beneficial. The outlook of the study is considered both near- and long-term (5 to 25 years). The approach was that of actively working with the Massachusetts Institute of Technology (MIT) Flight Transportation Laboratory and included interactions with "users" outside of both agencies as well as with organizations within. This report includes an overall survey of what are believed to be the causes of the capacity problems, ongoing work with the Federal Aviation Administration (FAA) to alleviate the problems, and identifies improvements in technology that would increase capacity and reduce delays.

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