FLIGHT TRANSPORTATION LABORATORY

REPORT R 91-7

IMPACTS OF TECHNOLOGY ON THE CAPACITY NEEDS OF THE U.S. NATIONAL AIRSPACE SYSTEM

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1. Introduction

Air passenger traffic in the United States showed remarkable growth during the economic expansion of the 1980's. Each day a million and a quarter passengers board commercial flights. The boom coincided with the advent of airline deregulation in 1978. This drastic change in the industry has inspired professional and newspaper articles, graduate student theses, and books which have discussed the causes, effects, costs, and benefits of deregulation with predictably mixed conclusions. Economists, who like to predict the future by exercising econometric models, are finding that conditions in air transportation have become too dynamic (chaotic?) for their models to cope. Certainly the future of the air transportation industry is unclear. There has been, however, an unmistakable trend toward oligopoly, or, as industry spokesmen describe it, "hardball competition among the major airlines." This trend has been accompanied by formations of hub fortresses owned by these survivors.

Air traffic has always been concentrated in a few large cities; airplanes will go where there is a demand for them. But airline (rather than traffic) hubs have created artificial demand. Up to seventy percent of travellers boarding airplanes in the hub cities do not live anywhere near these cities — in fact, they may have no idea at which airport they are changing planes. Most passengers do not care, while travel cognoscenti soon learn to avoid certain airports (and airlines which frequent these airports). A hub airport is a frenzy of activity for short periods of time during the day, as complexes of airplanes descend, park and interchange passengers, and take off. Then the airport lies quietly. If observers were to arrive at a major hub between times of complexes, they would be perplexed to hear that "this is one of the most congested airports in the world."

Thus congestion and its evil twin, delay, are not constants in the system. Rather, they appear only if a number of conditions conspire to manifest themselves simultaneously, or nearly so. First, the weather must deteriorate from visual flight conditions to instrument flight conditions. Then, this must occur near peak demand conditions at the airport. Of course, some airports in the Unites States are always near peak conditions, among them the so-called slot constrained airports: New York's La Guardia and Kennedy, Washington's National, and Chicago's O'Hare. When weather goes bad at these airports or other major hubs during complexes, ripple effects start nearly all over the country, because some airlines have now designed schedules to maximize utilization of their airplanes. Very little slack time is built into the schedules to account for potential delays, although "block-time creep" exists: the phenomenon that travellers discover when they arrive at their destinations ahead of schedule (if they happen to leave on time). This "creep" protects the airlines from being branded as laggards by the DOT's Consumer On-Time Performance Data hit list.

Thus a combination of management practices by airlines (which place great demand on terminal airspace over a concentrated period of time) and mother nature (which provides currently unpredictable behavior of weather near the airport) conspire to limit the capabilities to handle arrivals and departures at various airports below the numbers that had been scheduled. Travellers complain that the schedules aren't being met, and if enough people complain to Congress, or if the travellers themselves happen to be members of Congress, a national problem appears.

How much of a problem is this? In 1988 there were 21 airports, according to the FAA, which exceeded 20,000 hours of annual aircraft delay, perhaps 50,000 hours per year, or 140 hours per day. (One, Chicago's O'Hare, exceeded 100,000 hours.) These airports, in turn, averaged 1,000 operations (arrivals and departures) per day, so that each operation would have averaged about 8 minutes of delay. At O'Hare, for example, 6% of all operations experienced in excess of 15 minutes of delay. (In excess means just that — there is no knowledge of how much "in excess" is.)

Conversely, this means that at that most congested airport in the United States, 94% of all airplanes arrive or depart with less than 15 minutes of delay. However, airline delay statistics may be similar to the apocryphal story of the Boy Scout troop which drowned wading across a creek which averaged two feet in depth.

There are estimates that on a dollar basis, delay accounts for a $3 billion cost to airlines, or a net societal cost of $5 billion if travellers' wasted time is included. Since in their best years U.S. airlines make about $3 billion in profit, reducing delay is a sure-fire way for airlines to climb out of their all too frequent financial morasses, as well as diminishing their passenger frustrations.

Even though all of the numbers mentioned in the paragraphs above are subject to substantial caveats, it is indisputable that on certain days during the year the air transportation system seems to come to a crawl, if not a halt. Travellers either find themselves sitting at airport lounges observing cancellation and delay notices appearing on the departure and arrival screens, or sitting in airplanes (on runways or at gates) being told that there is an "air traffic delay." Old-timers grumble that the only difference twenty years of technology improvements has made to the U.S. airspace system is that the wait is now on the ground instead of circling in the air near their destinations.

To the casual observer, it would appear that a number of solutions exist to solve this problem. The most obvious is to pour more concrete: more airports, more and longer runways, more taxiways, more gates and terminals. This is analogous to widening highways and building more interstates for ground transportation congestion. The concrete solution, alas, runs into both financial and citizen roadblocks. It is very expensive — the latest airport coming off the drawing boards (Denver International) carries a tag of some $2 billion, with about $400 million of that in bonds being backed by a new funding creature, the Passenger Facility Charge (a head tax of up to 3 dollars assessed to every passenger enplaning at an airport — voluntary or not). The citizen roadblock is community objections to airport noisiness. The bill creating the PFC in 1990 also carried with it a mandate for the FAA to create a national noise policy so that individual airports would not wreak havoc with the whole system by creating their own local operational rules, such as curfews. The bill also attempted to pacify airport neighborhoods by setting a deadline for all U.S. aircraft to be quiet(er) — complying with Stage 3 regulations by the year 2000.

More damaging than financial difficulties are the anti-noise sentiments, and the concomitant not-in-my-backyard syndrome, that are at the forefronts of protests of either an alert citizenry, or New Age Luddites, when any expansion plans are made public. Whatever one's view, it is a crowd vocal and seemingly powerful enough in local political circles to stop any large- scale progress to ground solutions of the congestion problem. That, then, leaves the air.

It is intuitive that if airplanes were closer spaced than they are now, much more traffic would move through a given area in the same amount of time, and consequently airplanes would land (and take off) quicker, reducing any waiting (queue) time. This obviously increases airport noise levels. There are two problems with this approach. The first trick is to accomplish this safely. Safety has at least two dimensions: there is the physical, i.e., airplanes should not run into each other (or the ground, as a result of weather disturbances and wake vortices); and pilots (and controllers) should feel they are still in control of the situation, even after separation standards are reduced. The first aspect is mostly a matter of technology, the second mostly a matter of human factors. But if traffic moved quicker and noise of the aircraft is not reduced, the same citizens who had vehemently opposed the construction of additional ground facilities would once again rise in righteous anger and demand a stop to the more efficient techniques of flying airplanes which have caused an increase in the noise levels in their neighborhood. They, too, must be considered.

This report will attempt to address some of the issues outlined above. The focus will be on technology and where it is best suited to provide an equitable and efficient expansion of capacity in the air transportation system. Ultimately, the discussion will be centered on NASA's potential contributions to solving the capacity problem.*

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2. State of the Union

The air transportation system of the Unites States is huge by any measure. There are a lot of aircraft out there, most of them general aviation (222,000) and military (11,000). There are even a lot of rotorcraft: 7,000 civilian and 7,000 military. On the public side, the commuter fleet consists of 2,000 aircraft of various sizes from 8-seat props to 100-seat jets, while the commercial airline fleet contains about 4,000 jets. In 1990, U.S. airlines flew about 300 billion revenue passenger miles domestically (up from 100 billion in 1970), and another 100 billion internationally, while the airlines of the rest of the world flew 700 billion rpms.

While there are 17,000 airports in the U.S., only some four hundred have commercial service (Figure 1). These proportions reflect the general aviation and commercial uses of the total U.S. aircraft fleet. Only Australia has a similar number of airports with scheduled flights, while countries with large populations such as China, India, Indonesia and the old USSR have between 50 and 130 airports. Enplanements at airports are similarly weighted toward the U.S.; of the top ten airports in the world, Chicago (ORD), Dallas-Fort Worth, Los Angeles (LAX) and Atlanta are the top four, interrupted by London (Heathrow), Tokyo (Haneda), — followed by New York (JFK), San Francisco, Denver and finally Frankfurt. These numbers simply reaffirm that it is a country's GNP that drives aviation activity, rather than population or land area.

Airport activity can be characterized by either enplanements or aircraft operations. In the U.S., if measured by enplanements, the top twenty airports capture over fifty percent of passenger traffic. If airplanes are counted, the top twenty airports only account for sixteen percent of operations. This results from general aviation activity being spread more evenly over U.S. airports, while airline operations are much more concentrated at the hubs (Table 1). Overall, general aviation activity at the 400 airport traffic control towers across the U.S. has been around 40 million operations per year, or about 60% of all operations, while air carrier operations are about 20% (the rest being air taxi (15%) and military (5%), Table 2.)

When the last great airport capacity crunch appeared in the late 1960's, GA was a favorite villain, but there are very few small aircraft now at the largest hubs (Table

3). Attempts to banish them as a solution to congestion problems no longer have much merit, not to mention the stiff resistance from the Airplane Owners and Pilots Association.

In addition to reduced GA activity, the last capacity problem was resolved in part by growing aircraft size. From 1960, the number of seats per aircraft grew steadily from 65 to 110 in 1970 and finally peaked at 153 in 1983. It has stagnated there since as major airlines purchased smaller jet transports to feed their hub operations. The FAA forecasts that seating capacity will increase once again (Figure 2), and with the reduction in the number of airlines this in turn may alleviate traffic problems at the airline hubs.

GA operations still constitute a substantial portion of total operations at the good weather large hub airports (hubs defined by passenger enplanements), such as Denver, 6th largest hub, 22% GA operations; Phoenix, 8th, 25%; Honolulu, 14th, 25%; Miami, 15th, 19%; Orlando, 18th, 15%; Las Vegas, 21st, 29%. (Tables 4 & 5).

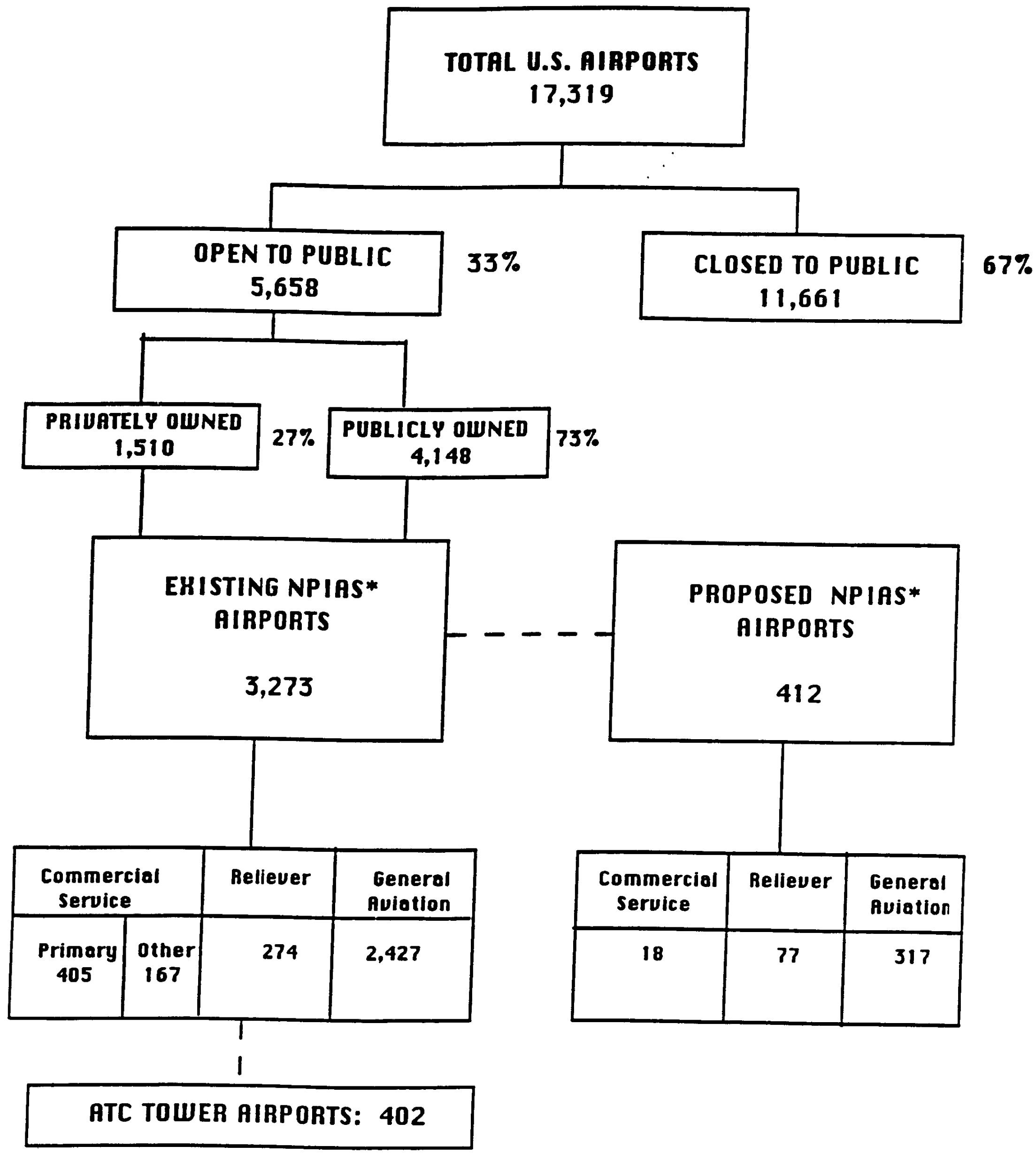
Finally, of the 20 airports which the FAA considers capacity limited, two, Long Beach and Santa Ana in California, are primarily general aviation airports (82% of operations at SNA and 93% at LGB) (Tables 5 and 6). Thus lack of capacity is not considered to be exclusively an air carrier airport problem.

Since the 1960's FAA has also attempted to create capacity through the designation of some GA airports as reliever airports, which allowed them easier access to FAA funds. The 1990 FAA Aviation System Capacity Plan notes that, ". . . Reliever airports can be expected to play significant roles in reducing congestion and delay at delay-problem airports, especially those where general aviation constitutes a significant portion (over 25%) of operations." But while reliever airports can certainly divert more GA traffic from airports which simultaneously have large GA activity and delay-problems (13 of 41 expected delay problem airports by 1998, according to the FAA's forecast), these are not the airports that are the problem sites of the system. The largest delays are at the largest airline hubs, starting with O'Hare (Figure 3).

Although there was a small amount of airline hubbing before deregulation in 1978 (at Atlanta, Chicago, Dallas-Fort Worth and Denver), most trunk airlines were restricted by their route authority to fly only a few of the denser routes out of major

FIGURE 1.

NUMBER OF AIRPORTS BY OWNERSHIP & PUBLIC USE (1989)



* NATIONAL PLAN OF INTEGRATED AIRPORT SYSTEMS

SOURCE: FAA

TABLE 1.

CONCENTRATION AT U.S. AIRPORTS

(FY1989)

ENPLANEMENTS	(% OF TOTAL)	OPERATIONS	(% OF TOTAL)
TOP FIVE (ORD, DFW, LAX, ATL, JFK)	23.1%	TOP FIVE (ORD, DFW, ATL, LAX, SNA)	5.4%
TOP TWENTY	55.1%	TOP TWENTY	16.0%
TOP THIRTY (LARGE HUBS)	67.5%	TOP THIRTY	21.9%
TOP FIFTY	81.4%	TOP FIFTY	31.1%
TOP SEVENTY-ONE (LARGE AND MEDIUM HUBS)	88.5%		
TOP ONE HUNDRED AND THIRTY FIVE (LARGE, MEDIUM, AND SMALL HUBS)	95.7%	TOP ONE HUNDRED (BY ENPLANEMENTS)	40.9%
TOTAL ENPLANEMENTS:	483.1 million	TOTAL OPERATIONS: (at 400 ATC towers)	61.35 million

* SOURCE: FAA Aviation Forecasts, 1991-2002

TABLE 2. TOTAL NATIONAL AIRSPACE SYSTEM ACTIVITY

	1990	1995	2000	2005	Percent Growth 1990 - 2005
NPIAS Airports *	3320	3560	3800	4100	23.5
Airport Operations (millions)					
Aircraft Operations	143.9	165.0	183.8	201.7	40.2
Itinerant Operations	84.6	99.0	111.3	123.2	45.6
Instrument Operations	46.4	53.4	58.6	63.8	37.5
Towered Airport Operations	62.8	70.9	78.0	84.5	34.6
Military Airport Operations	28.6	29.6	30.5	30.5	6.6
ARTCC Operations (millions)					
IFR Aircraft Handled	37.8	42.8	46.9	50.6	33.9
ACF Approach Control Operations**	---	---	58.6	63.8	---
FSS Service (millions) Flight Plans, Radio Contacts, Briefings	44.9	45.8	47.1	48.1	7.1
Hours Flown (millions) Air Carrier	10.6	12.1	13.1	14.2	34.0
General Aviation	34.0	37.0	39.9	41.8	22.9
Military	6.0	6.1	6.2	6.2	3.3
Domestic Enplanements (Revenue Passenger) (millions) Air Carrier	430.6	529.6	645.3	849.1	97.2
Commuter	34.9	49.5	67.3	86.0	146.4
Aircraft Fleet (thousands)					
Air Carrier	4.1	4.5	4.8	5.2	26.8
Commuter***	1.8	2.0	2.2	2.4	33.3
Total General Aviation	212.9	218.2	221.7	224.4	5.4
Civil Helicopter***	7.0	8.6	10.3	12.1	72.9
Total Military	19.1	18.1	18.0	18.0	(5.8)
Military Helicopter***	7.4	6.0	6.0	6.0	(18.9)
Pilots (thousands)					
Instrument Rated	278.7	297.0	312.0	325.0	16.6
Total Pilots	704.3	747.2	779.6	811.0	15.1

* Aircraft operations forecasts are based on the existing airports included in the National Plan on Integrated Airport Systems (NPIAS).

** Approach control operations conducted for area control facilities equal the number of instrument operations conducted by towers.

*** Civil helicopter and commuter fleets are included in the Total General Aviation Fleet. The military helicopter fleet is included in total military fleet.

Source: Aviation System Capital Investment Plan, FAA, December 1990.

TABLE 3.

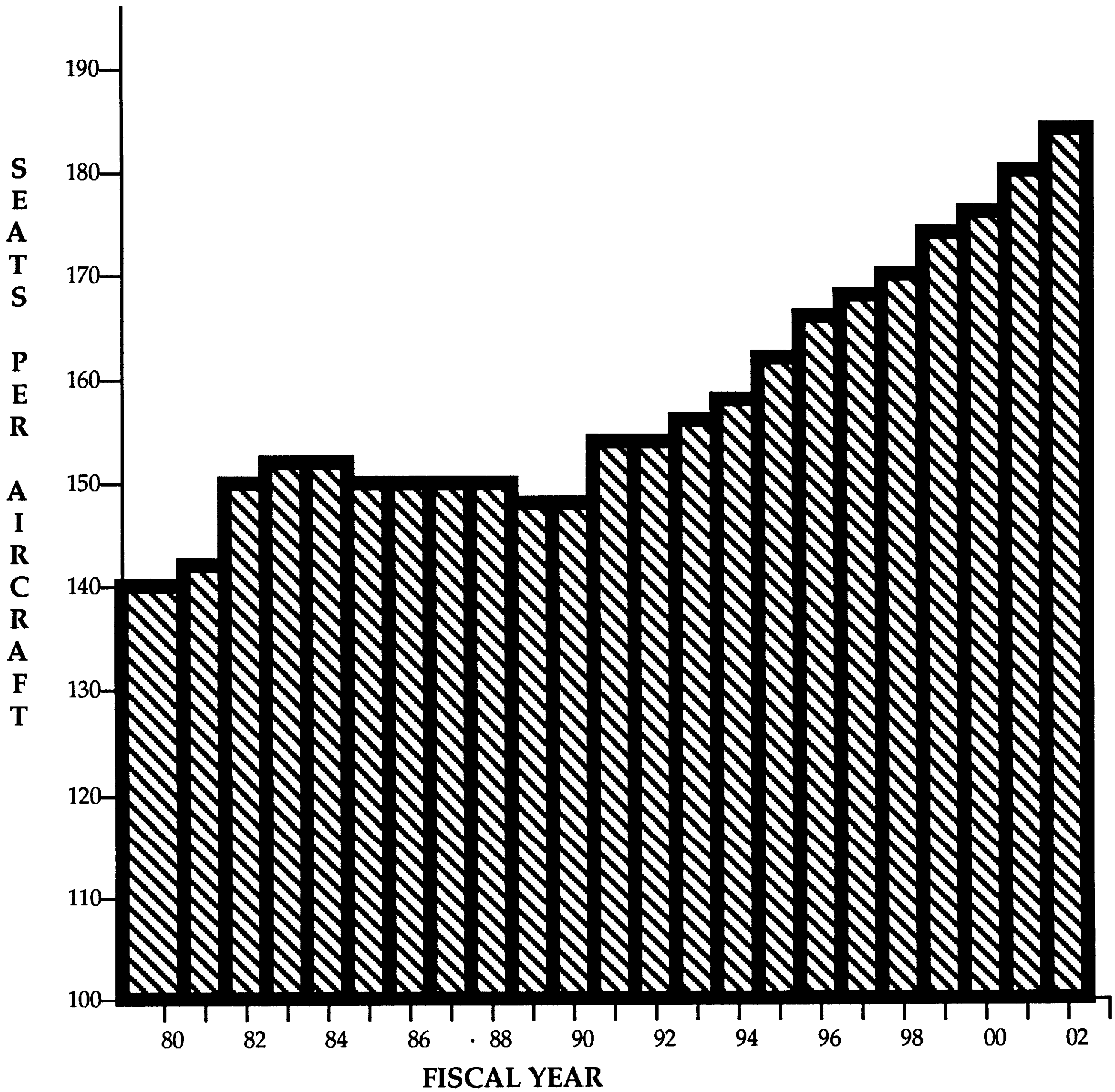
TOP 25 FAA-OPERATED AIRPORT TRAFFIC CONTROL TOWERS, BY RANK ORDER OF AIR CARRIER OPERATIONS AND BY AVIATION CATEGORY INCLUDING TOTAL OPERATIONS RANK FISCAL YEAR 1989

Tower	Air Carrier		Air	General	Military	Total	
	Rank	Operations	Taxi	Aviation		Rank	Operations
Chicago O'Hare Int'l	1	620,090	137,411	28,266	3,587	1	789,384
Dallas Ft. Worth Reg'l	2	505,822	168,258	18,501	1,033	2	693,614
Atlanta International	3	478,290	165,223	24,730	1,300	3	669,543
Los Angeles International	4	427,419	151,785	47,981	5,052	4	632,237
Denver Stapleton Int'l	5	323,165	104,560	38,911	1,854	9	468,490
San Francisco	6	311,430	85,209	35,096	2,563	11	434,398
Phoenix Sky Harbor Int'l	7	285,493	66,214	119,977	8,106	8	479,790
St. Louis Int'l	8	283,436	93,644	39,768	8,409	12	425,257
Newark	9	269,839	82,197	24,201	552	23	376,789
Detroit Metro Wayne Co	10	269,199	47,176	52,312	210	25	368,897
La Guardia	11	262,784	65,426	26,904	454	27	355,568
Pittsburgh Greater Int'l	12	249,081	96,751	25,898	6,801	20	378,531
Miami Int'l	13	247,356	55,208	70,541	5,152	21	378,257
Boston Logan	14	239,281	131,519	45,952	319	14	417,111
Minneapolis St. Paul Int'l	15	230,656	76,290	64,299	4,994	24	376,239
Charlotte Douglas	16	229,199	111,862	79,150	3,806	13	424,017
John F. Kennedy Int'l	17	220,467	91,220	24,339	705	29	336,731
Houston Intercontinental	18	207,163	44,601	41,217	1,030	36	294,011
Memphis International	19	197,470	58,303	71,731	6,957	30	334,461
Honolulu	20	195,981	67,022	99,641	43,466	15	406,110
Orlando International	21	190,921	48,726	41,558	4,432	38	285,637
Washington National	22	185,580	55,962	74,346	250	33	316,138
Las Vegas McCarran	23	183,362	78,700	109,022	7,033	22	378,117
Philadelphia Int'l	24	181,342	142,386	57,700	851	19	383,279
Seattle Tacoma	25	180,145	134,012	13,248	400	31	327,805

Note: Total Operations rank was based on total air traffic activity at 400 FAA-Operated Towers. Air Carrier operations rank was based on air carrier activity at 309 FAA-Operated Towers. Not all FAA-Operated Towers handle air carrier operations.

Source: FAA Statistical Handbook of Aviation, CY 1989

FIGURE 2.
U.S. Commercial Carriers
Seats Per Aircraft - Domestic Service



Source: FAA Forecast Conference 1991

TABLE 4.

**TOP 30 AIRPORTS
IN RANK ORDER BY TOTAL ENPLANED PASSENGERS
LARGE SCHEDULED CERTIFICATED AIR CARRIERS
SCHEDULED AND NONSCHEDULED OPERATIONS
1989**

Rank	Airport	Total Enplaned Passengers
1	Chicago (O'Hare), IL	25,664,266
2	Dallas/Ft/ Worth (Regional), TX	22,623,065
3	Atlanta, GA	20,397,697
4	Los Angeles, CA	18,583,292
5	San Francisco, CA	13,326,085
6	Denver, CO	12,320,246
7	New York (La Guardia), NY	10,839,833
8	Phoenix, AZ	10,166,095
9	New York (John F. Kennedy), NY	10,081,490
10	Newark, NJ	9,822,419
11	Detroit, MI	9,739,265
12	Boston, MA	9,661,258
13	St. Louis, MO	9,396,335
14	Honolulu, Oahu, HI	8,943,521
15	Miami, FL	8,591,936
16	Minneapolis/St. Paul, MN	8,460,115
17	Pittsburgh, PA	7,940,962
18	Orlando, FL	7,373,449
19	Seattle-Tacoma, WA	7,059,777
20	Houston (Intercontinental), TX	7,030,001
21	Las Vegas, NV	7,026,900
22	Charlotte, NC	6,903,482
23	Washington (National), DC	6,895,563
24	Philadelphia, PA	6,247,489
25	San Diego, CA	5,317,177
26	Salt Lake City, UT	5,244,238
27	Washington (Dulles Int'l), DC	4,543,530
28	Baltimore, MD	4,446,139
29	Tampa, FL	4,409,261
30	Kansas City, MO	4,356,991

Source: FAA Statistical Handbook of Aviation, CY 1989

TABLE 5.

TOP 25 FAA-OPERATED AIRPORT TRAFFIC CONTROL TOWERS,
BY RANK ORDER OF TOTAL OPERATIONS
AND BY AVIATION CATEGORY INCLUDING AIR CARRIER RANK
FISCAL YEAR 1989

Tower	Total		Air Carrier		Air Taxi	General Aviation	Military
	Rank	Operations	Rank	Operations			
Chicago O'Hare Int'l	1	789,384	1	620,090	134,441	28,266	3,587
Dallas Ft. Worth Reg'l	2	693,614	2	505,822	168,258	18,501	1,033
Atlanta International	3	669,543	3	478,290	165,223	24,730	1,300
Los Angeles International	4	632,237	4	627,419	151,785	47,981	5,052
Santa Ana	5	533,522	55	62,302	27,727	438,161	5,332
Van Nuys	6	499,087	262	21	774	496,473	1,819
Fort Worth Meacham	7	492,743	235	148	1,599	490,512	484
Phoenix Sky Harbor Int'l	8	479,790	7	285,493	66,214	119,977	8,106
Denver Stapleton Int'l	9	468,490	5	323,165	104,560	38,911	1,854
Long Beach	10	462,177	94	20,048	7,656	431,683	2,790
San Francisco	11	434,298	6	311,430	85,209	38,096	2,563
St. Louis Int'l	12	425,257	8	283,436	93,644	39,768	8,409
Charlotte Douglas	13	424,017	16	229,199	111,862	79,150	3,806
Boston Logan	14	417,111	14	239,281	131,519	45,992	319
Honolulu	15	406,110	20	195,981	67,022	99,641	43,466
Seattle Boeing	16	404,626	143	7,934	20,376	373,365	2,951
Oakland International	17	403,213	49	74,682	57,281	270,284	966
Pontiac	18	401,819	241	114	8,884	392,018	803
Philadelphia Int'l	19	383,279	24	181,342	143,386	57,700	851
Pittsburgh Greater Int'l	20	378,531	12	249,081	96,751	25,898	6801
Miami Int'l	21	378,257	13	247,356	55,208	70,541	5,152
Las Vegas McCarran	22	378,117	23	183,362	78,700	109,022	7,033
Newark	23	376,789	9	269,839	82,197	24,201	552
Minneapolis St. Paul Int'l	24	376,239	15	230,656	76,290	64,299	4994
Detroit Metro Wayne Co	25	368,897	10	269,199	47,176	52,312	210

Note: Total Operations rank was based on total air traffic activity at 400 FAA-Operated Towers. Air Carrier operations rank was based on air carrier activity at 309 FAA-Operated Towers. Not all FAA-Operated Towers handle air carrier operations.

Source: FAA Statistical Handbook of Aviation, FY 1989

Table 6. Airports Currently Experiencing Capacity Problems

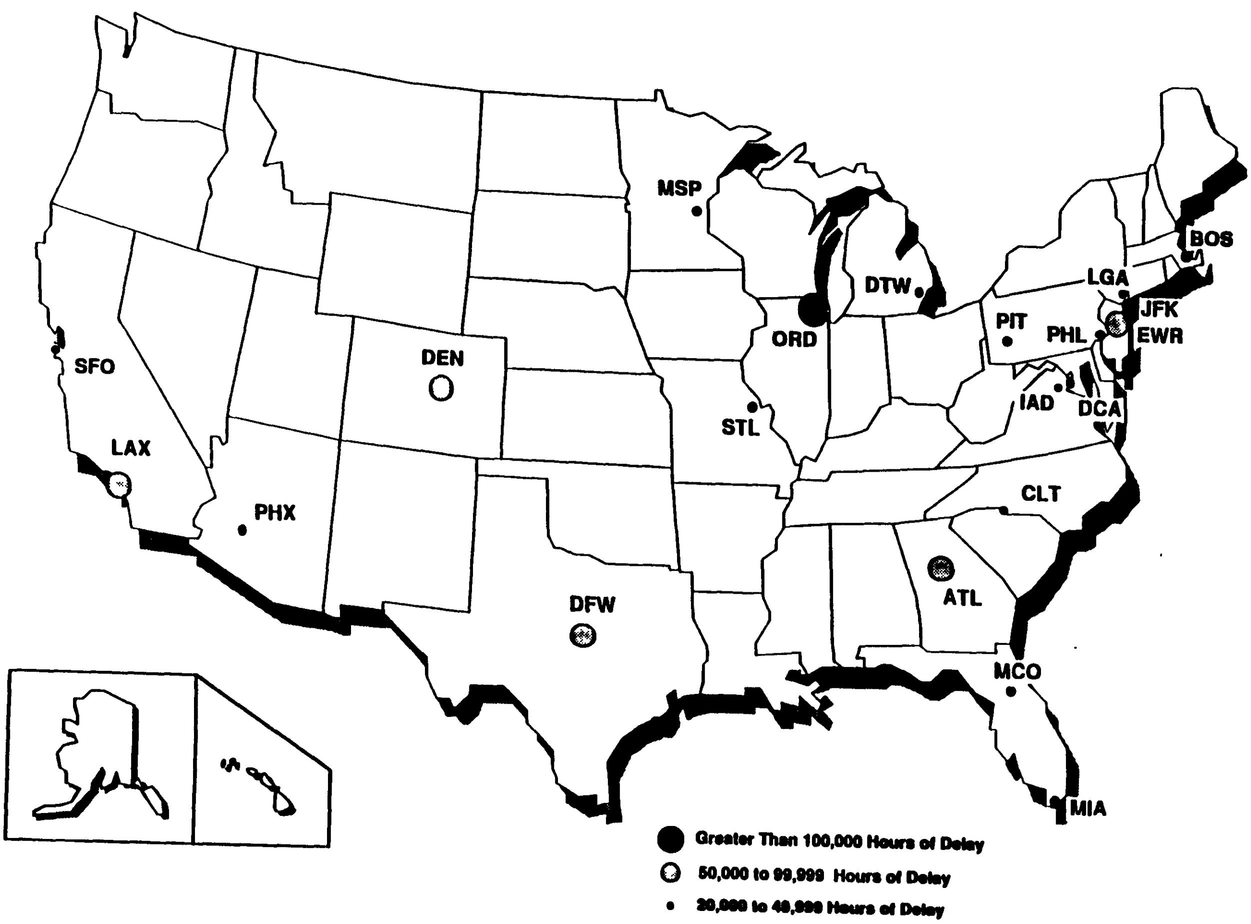
(As of Calendar Year 1989)

Atlanta, GA	Hartsfield	Newark, NJ	International
Burbank, CA	Burbank	New York, NY	Kennedy
Boston, MA	Logan	New York, NY	LaGuardia
Chicago, IL	O'Hare	Philadelphia, PA	International
Dallas/Fort Worth, TX	International	Phoenix, AZ	Sky Harbor
Denver, CO	Stapleton	Raleigh, NC	Raleigh-Durham
Houston, TX	Intercontinental	San Francisco, CA	International
Las Vegas, NV	McCarran	Santa Ana, CA	John Wayne
Long Beach, CA	Dougherty Field	St. Louis, MO	Lambert
Los Angeles, CA	International	Washington, DC	National

Source: Aviation System Capital Investment Plan, FAA, December 1990.

FIGURE 3.

AIRPORTS EXCEEDING 20,000 HOURS OF ANNUAL AIRCRAFT DELAY IN 1988



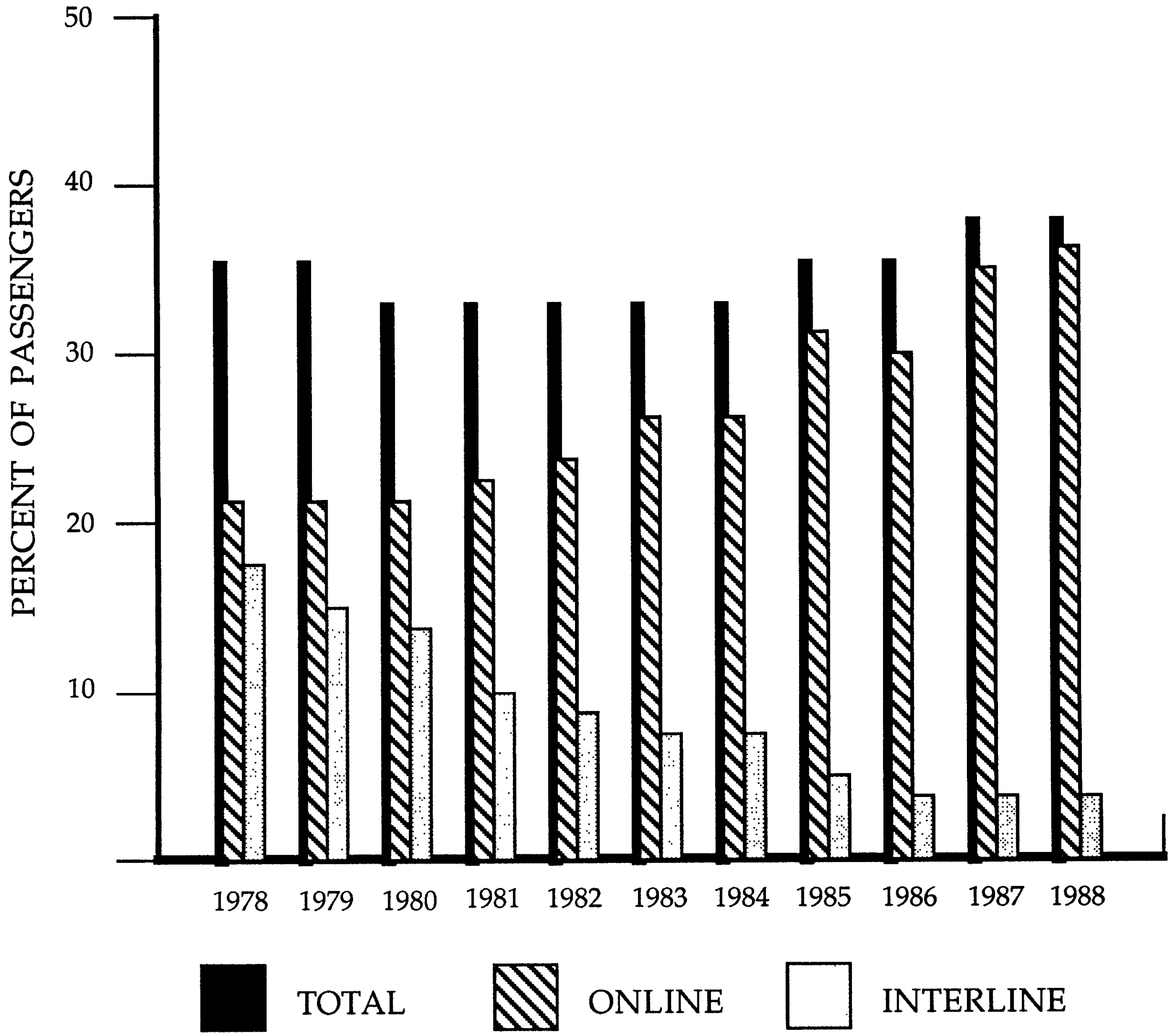
SOURCE: FAA 1990 - 91 Aviation System Capacity Plan cities. The local service airlines carried the passengers from one of the larger cities to the smaller airports in the region. Often there was no choice for the passenger, and if the trunks did have small cities on their route systems, they provided desultory service, allowing the local service carriers to flourish. The same phenomenon allowed commuter air carriers to pick off the even smaller cities on the locals' routes. Prior to deregulation, interlining (i.e., passengers changing airlines during a trip) amounted to half of all connecting traffic.

After deregulation, not everyone was quick to organize hub-and-spoke networks. United Airlines' first strategic move was to rid itself of service to smaller cities (and attempting to discard smaller aircraft) and concentrate on service between larger cities, depending on the locals to continue to feed United's main routes. But the locals would no longer play this game and began expanding their networks to carry "their" (originating) passengers to their final destinations on their new (more profitable) longer hauls. As locals began gaining market share, United and other trunks fought back by either buying smaller aircraft and expanding their hub-and-spoke networks (American Airlines), or by simply buying out the competition (TWA, Northwest, US Air). Lax enforcement of anti-trust laws and imaginative marketing techniques (frequent flier miles and yield management) helped the remaining trunks (now called majors, i.e. airlines with $1 billion in revenue) regain and exceed their pre-deregulation market share. Although connecting traffic has remained at around forty percent, there is practically no interlining now, showing how adept the airlines have become at holding on to their passengers (Figure 4). At the same time, transfer traffic has created most large traffic hubs by generating artificially high enplanement counts (Figure 5). Some of the largest hubs have connecting traffic exceeding originating traffic: SLC, DEN, DFW, STL, ATL, CLT, PIT, with MSP and ORD close behind. Because of the density of traffic, even in the coastal cities there are large numbers of passengers changing planes (6 million plus in New York, San Francisco and Los Angeles), though the transfer percentages are not high.

As the number of airline hubs has grown from four in 1978 to thirty-two in 1990 (Figures 6 and 7), the percentage of airline traffic touching down at at least one hub has increased from 50% in 1978 to 88% in 1990 (Figure 8). Since these hubs have such a large percentage of the total U.S. airline operations, and an even larger percentage of total passengers, deteriorating weather conditions which always

Figure 4.

PERCENT OF DOMESTIC PASSENGERS
USING CONNECTING SERVICE

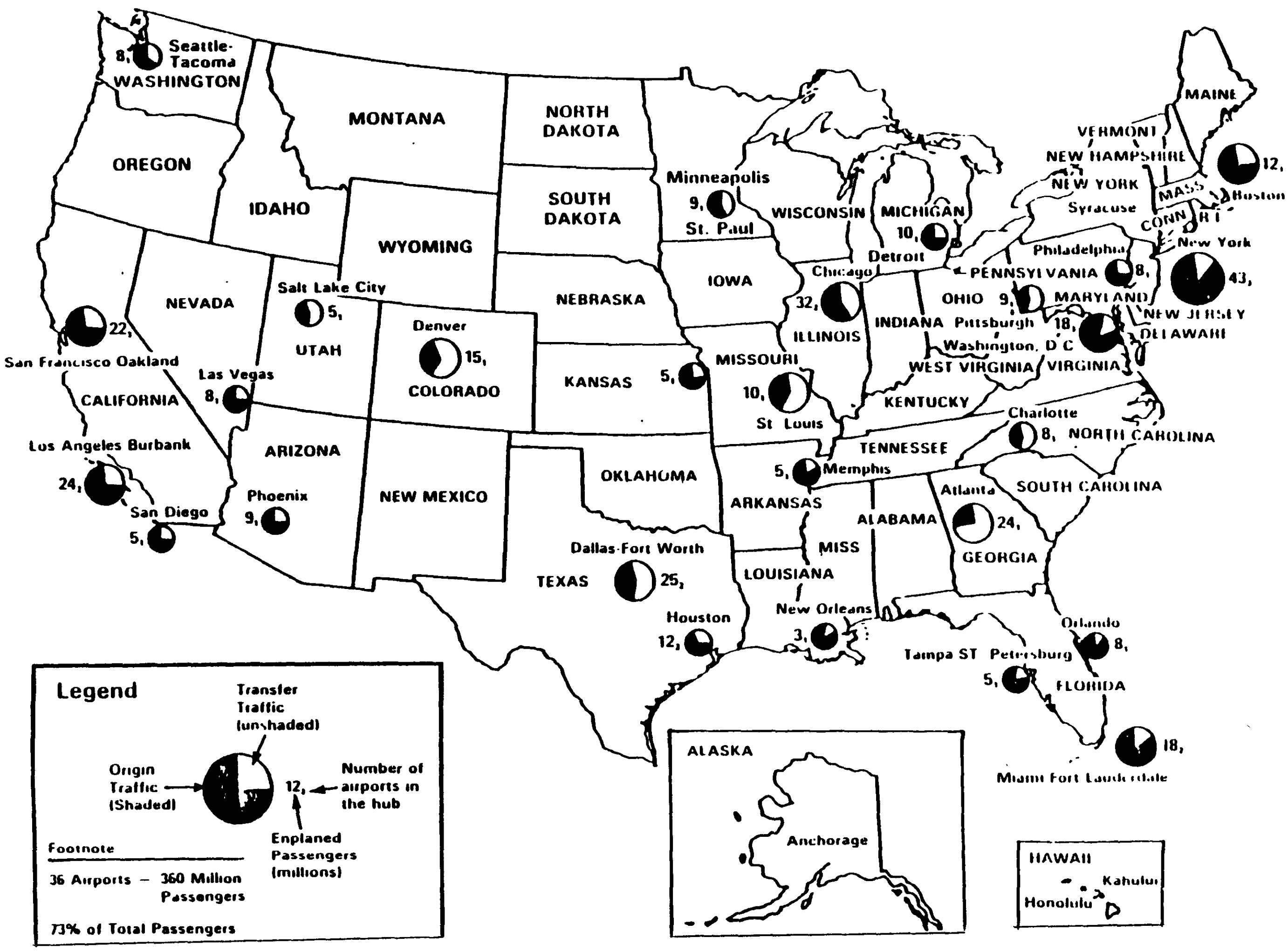


SOURCE: CAB/DOT SURVEY

FIGURE 5.

27 AIR TRAFFIC HUBS

(BUSIEST MARKETS)



SOURCE: Emily A. White, TRB Annual Meeting Session 46, 1991

FIGURE 6.

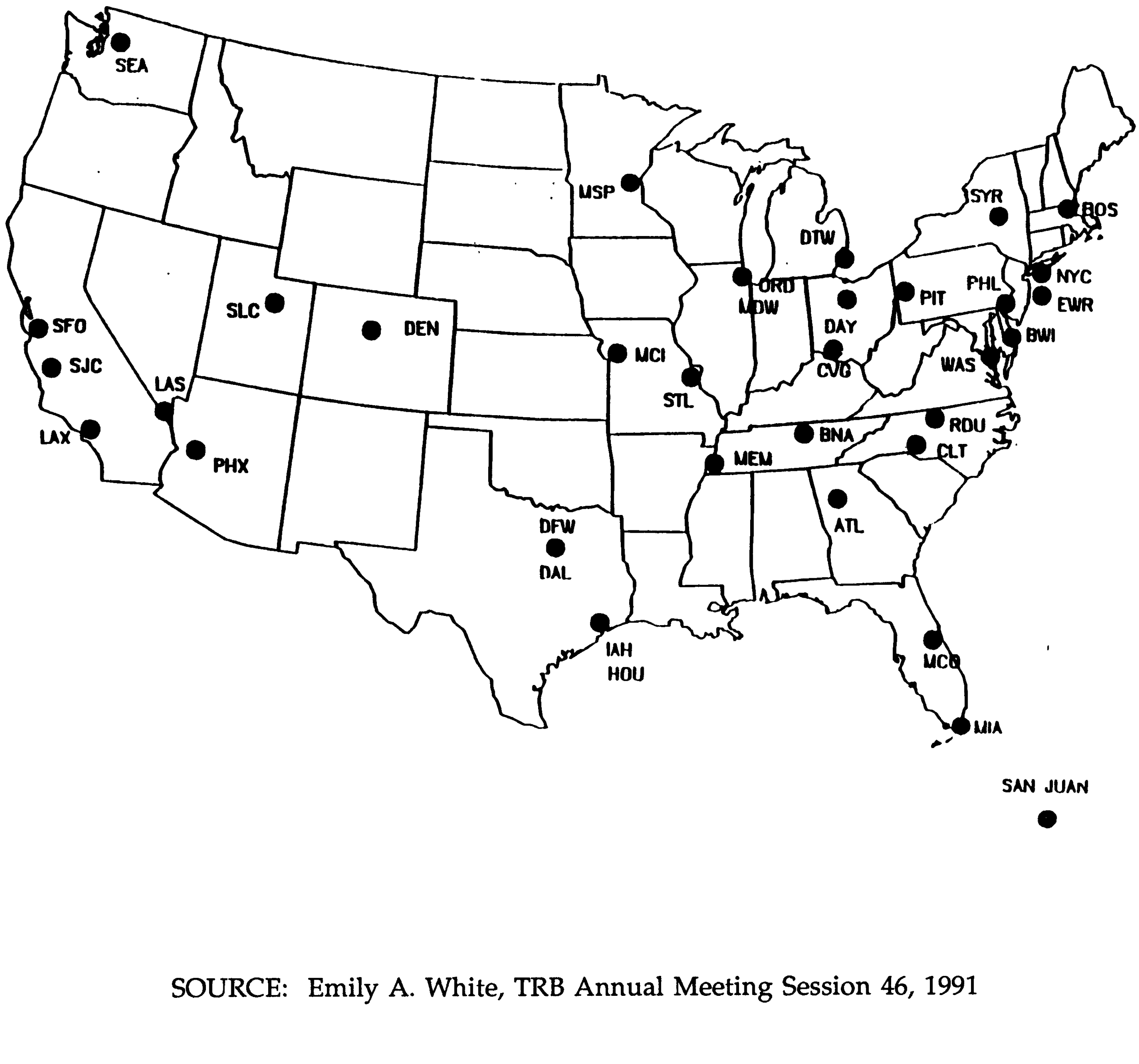
MAJOR AIRLINE HUBS

PRIOR TO 1978

SOURCE: Emily A. White, TRB Annual Meeting Session 46, 1991

FIGURE 7.

MAJOR AIRLINES 1990 HUBS

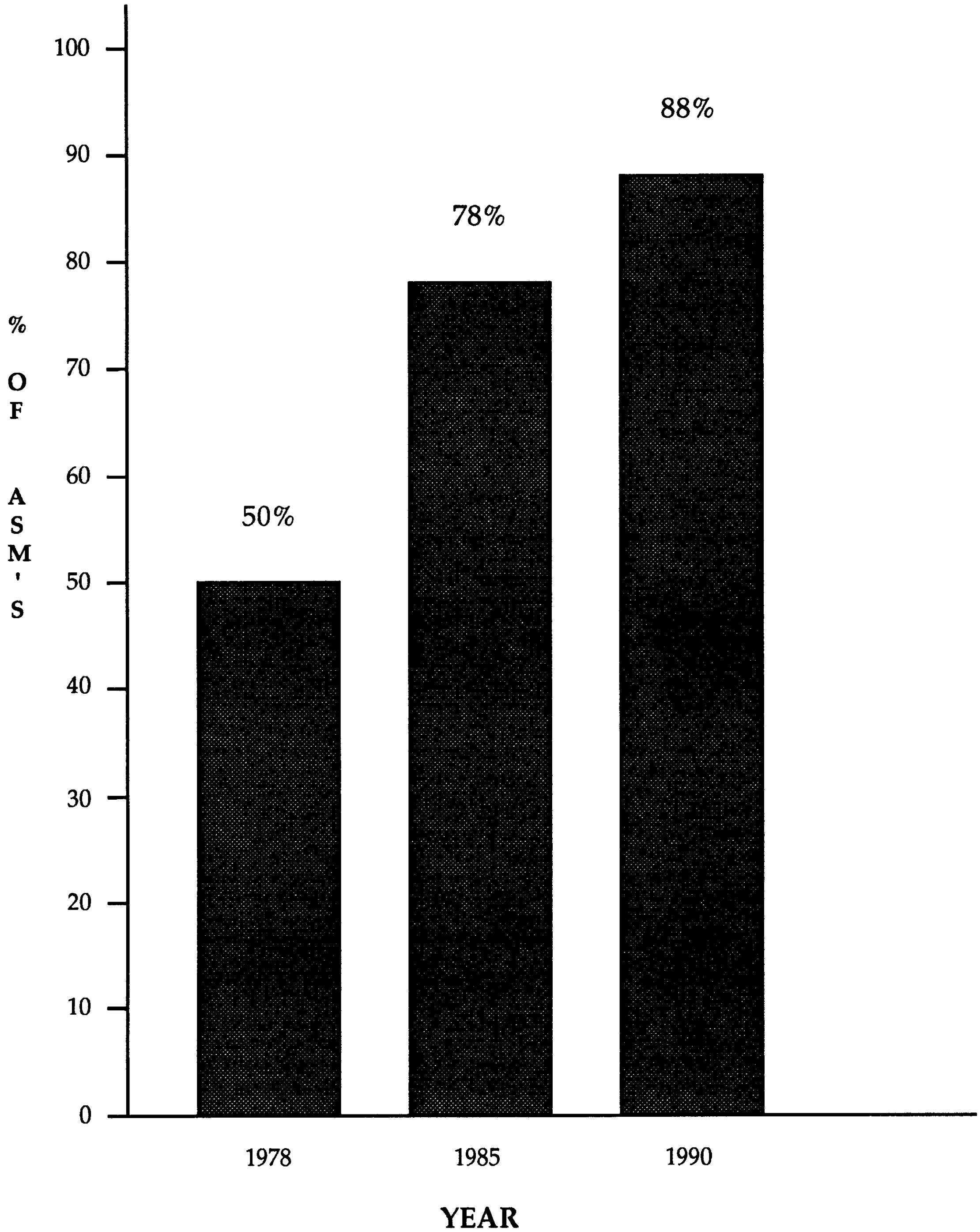


SOURCE: Emily A. White, TRB Annual Meeting Session 46, 1991

FIGURE 8.

% OF DOMESTIC CAPACITY RELATED TO HUBS

U.S. Major Carriers



Source: Delta Airlines, 1991, FAA Forecast Conference reduce the operational capacity at these airports create traffic jams for aircraft and travellers all over the U.S. A cursory look at "the capacity problem of the United States" leads only to the "usual suspects", the large hubs, creating suspicions about the potential exaggeration of this issue.

Partially to alleviate these dangers of possible overstatements, in almost all discussions about capacity and delay in the U.S. airspace system, a distressingly large amount of time is spent on defining the terms in question. Often the discussion bogs down right from the beginning as the participants are unable to agree on precise definitions of the very basic words: capacity, delay, and congestion. For example, the FAA finesses the definition of capacity and congestion altogether:

> The first step in a problem-solving exercise is problem definition. This plan defines the aviation capacity problem in terms of flight delays rather than dealing with the more abstract "capacity" definition. While it is relatively simple to compute an airport's hourly throughput capacity (the *average* number of flight operations which can be handled in IFR or VFR for a given runway operating configuration), annualizing these numbers is more difficult. The term "congested airport" is a term of art, not science.[1]

In general, airport capacity is a function of airport design (number and direction of runways and taxiways, runway instrumentation, etc.), weather conditions (VFR vs. IFR and wind directions), aircraft mix, and ATC procedures (sequencing and spacing of aircraft). When airline and GA activities exceed the ability of the airport to accept and release aircraft, delays occur. They occur because airlines schedule too many arrivals and departures during a given time period; because of deteriorating weather conditions which reduce the runway system capacity; because of the aircraft mix, both arriving and departing; or, usually, because of some combination of the above conditions. Thus delay in the most general sense is a function of both capacity and demand.

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1 Federal Aviation Administration, "1990-91 Aviation System Capacity Plan," Washington, DC, 1990, p. 6-1.

The occurrence of delays is an acknowledged fact. However, it is the magnitude of the problem, i.e., just how much "time is lost due to delays," that is subject to question. Over the years, many organizations have tried to quantify delay: the FAA, the DOT, the airlines, and various airport authorities. Each of these entities has had a different reason to measure what it perceives to be the critical component of time lost in unproductive activity. Consequently, each has focused on different delay statistics.

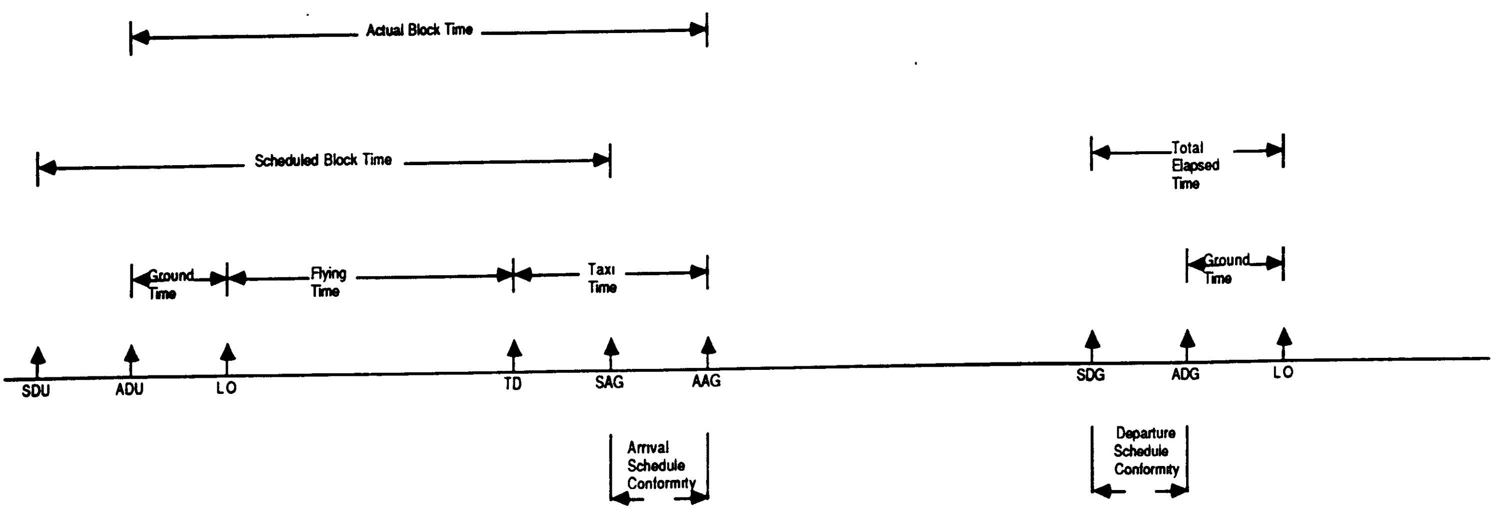
Airports are generally interested in how much delay occurs within their jurisdictions (and usually relative to other airports). For example, the Port Authority of New York and New Jersey has worked with TWA and American Airlines at JFK, LGA and EWR since the late 1960's to devise delay statistics which are used as airport performance measures (Figure 9.). The statistics on arrival and departure schedule conformity at New York/New Jersey airports have shown predictable seasonality patterns (increases during winter and summer vacation seasons at EWR, LGA, and summer international peaks at JFK), superimposed on unpredictable variations due to aircraft component failure and bad weather. This type of data shows that most NY/NJ <u>airport</u> delay indicators have remained largely unchanged from 1985 to 1990.

The three major delay data collection systems have been maintained by the DOT/FAA. The most recent one, "Air Carrier On-Time Flight Performance Data," is a result of Congressional pressure on the DOT to give the consumer a better idea of which carrier (or, at the most detailed level, which flight) meets its schedule best, both arriving and departing. Data is provided monthly to the DOT by the top dozen airlines for their schedules into selected (largest) U.S. airports. These numbers do not have associated with them any causes of delay, and consequently are useless for air traffic congestion analysis. Furthermore, as is also the case with all other data bases, mechanical delays are excluded from the DOT data. Only the airlines know for sure how much of a problem is caused by unreliable aircraft; a commonly accepted number is 5% of total delays.

The other two delay data bases have been maintained by different branches of the FAA, Air Traffic Operations Management System (ATOMS) [previously known as OPSNET and NAPRS] and Standardized Delay Reporting System (SDRS). ATOMS relies on air traffic controller observations; SDRS relied on delay reports submitted

FIGURE 9.

DELAY STATISTICS AT PORT AUTHORITY OF NY AND NJ AIRPORTS



SDU = Scheduled Departure, Upline
ADU = Actual Departure, Upline
LO = Lift-Off

TD = Touchdown
SAG = Scheduled Arrival, Gate
AAG = Actual Arrival, Gate

SDG = Scheduled Departure, Gate
ADG = Actual Departure, Gate
LO = Lift-Off

SOURCE: Port Authority of NY and NJ

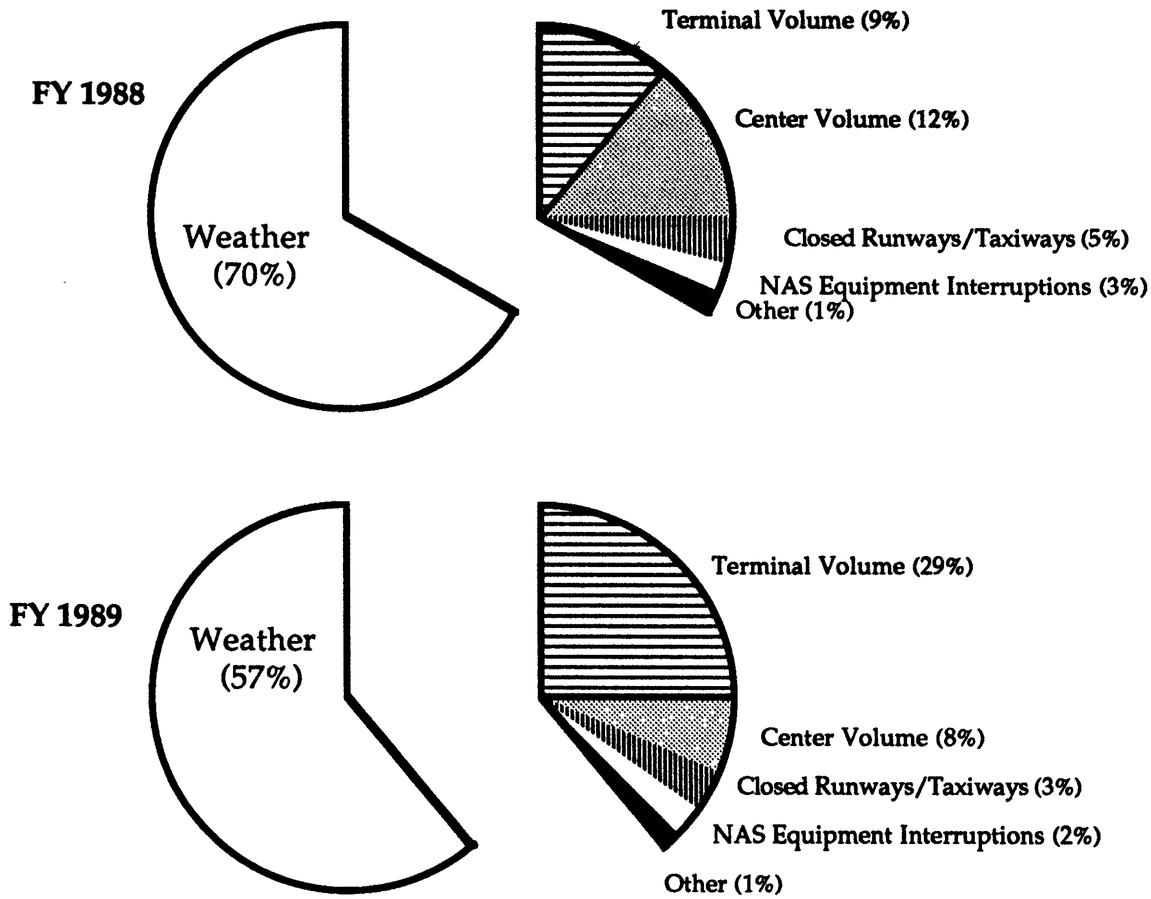
by American, Eastern and United Airlines. Each of these systems, while useful in its way, has some faults when used for airspace capacity definition or analysis.

ATOMS defines a delay as an aircraft flight for which there is a period of 15 minutes or more between a request for permission to taxi and actual takeoff (departure delay), a period of 15 minutes (or more) between a request for permission to land and actual landing (arrival delay), or a departure delay of 15 minutes or more at an airport because of conditions at a destination airport (gate hold). Some deficiencies of ATOMS are: (a) it does not include delays shorter than 15 minutes, so that most delays are never recorded, and the system seriously underestimates total delay; (b) it fails to track cumulative delays of individual flights; (c) since it depends on controller observations, the actual gate departure/arrival times are not noted at those airports where controllers only take over after aircraft reach taxiways; (d) and since it depends on controller observations, there can be wide variability among towers depending on how much priority the recording and accuracy of delay data has. ATOMS confirms that weather is the main culprit in causing delay (Figure 10).

SDRS defined delay as the difference between optimal (nominal) and actual flight times, to the closest minute, recorded by four phases of flight: gate-hold, taxi-out, airborne, and taxi-in. The three reporting airlines and the FAA agreed upon nominal intervals (for each aircraft type) and for individual airport procedures; if there was a deviation during each phase from the nominal it was considered as delay. (A nominal flight time from gate to gate was the time it should take without other aircraft in the system or problems with ATC equipment or weather.) The system only reported where delay occurred, not the cause: for example, delay in the air can be caused by ground congestion at the destination, gate-holds can be caused by congestion at the departure airport, en route airspace, or destination airport congestion. (There was a bias built into the system if an airport had multiple terminal entry points and only one runway configuration was considered as standard.) The SDRS data did not reflect at all variations in flight times from airline flight <u>schedules</u>; it only reflects the ability of the ATC system to deal with aircraft once they are accepted into the system by the FAA. Since the demise of Eastern and drop-out of United, SDRS is now simply an historical record. SDRS indicated that airline delays averaged 11.8 minutes per flight in 1980 and 15.6 in 1988, with most of the increase taking place before 1987.

Figure 10.

Primary Cause of Delay of 15 Minutes or More in FY88 and FY89



Source: FAA 1990 - 91 Aviation System Capacity Plan

Airport capacity is not a single number, nor is the U.S. airport system capacity a summation of mythical individual airport capacities. Capacity definitions begin with runway capacity. One practical definition is "maximum throughput" or "saturation" hourly capacity, the number of operations that can be conducted during an hour at a runway without violating ATC rules and assuming continuous aircraft demand. Since larger separations (in distance) exist between aircraft arrivals and longer (in time) between aircraft departures exist in IFR than in VFR (assuming the same aircraft mix), there will be different IFR and VFR hourly capacities for a single runway. While single runway capacities only vary by some 25% depending on visual conditions, dual runways have more than 50% differences, presaging the much larger total airport capacity variations (Figures 11, 12 and Table 7).

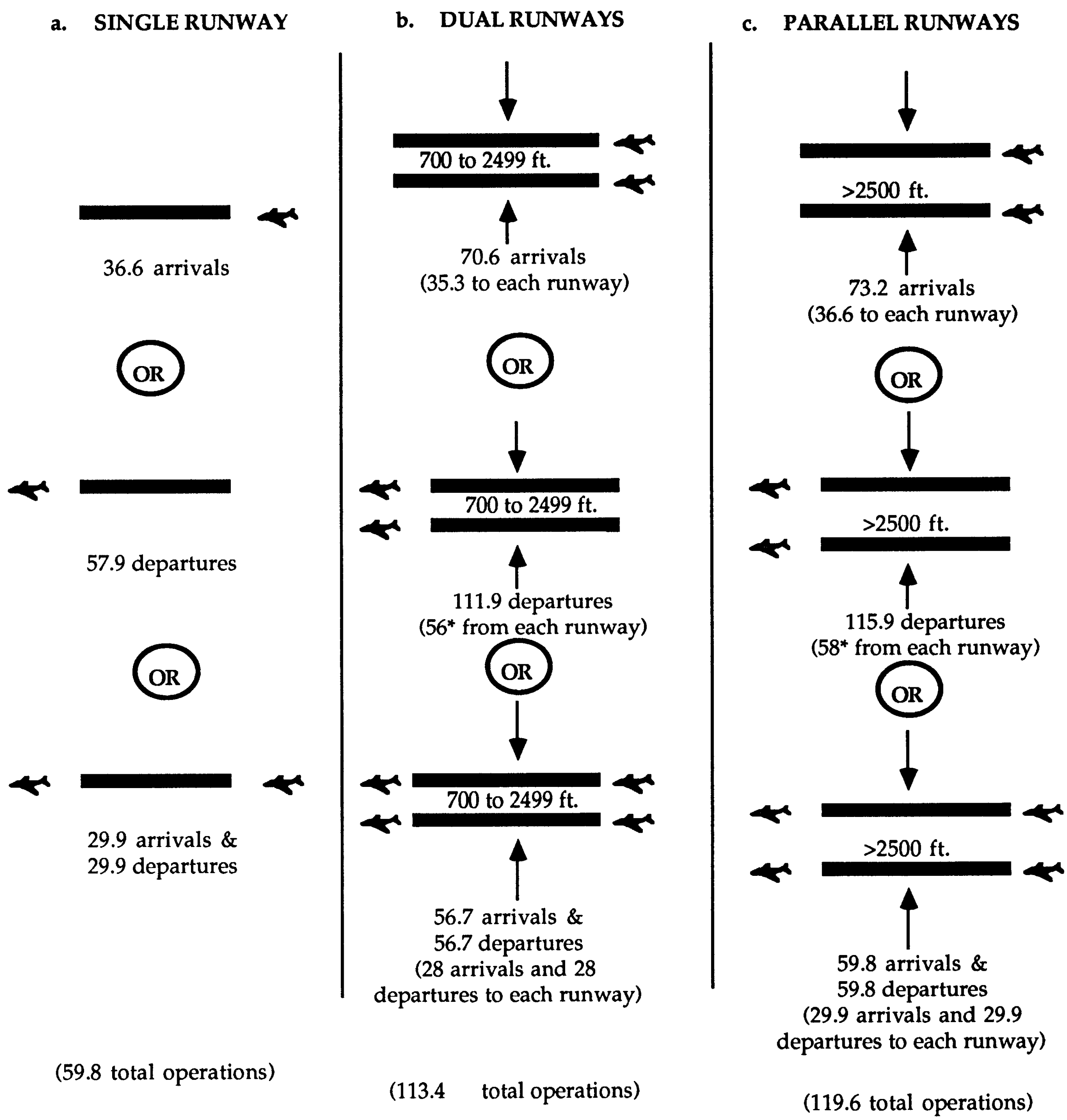
Given a set of runways at an airport, airplanes can land using different combinations of runways depending on wind direction, wind speed, and visibility conditions. Length of runways is also important if the aircraft mix at the airport is such that <u>some</u> aircraft require specific runways, i.e., heavy long range aircraft need long runways. Major airports may have fifty or more combinations of runway use, and each of these has some capacity number attached to it. Furthermore, since practically all the factors that affect airport capacity are variable, hourly capacity itself is highly variable. Usually the stated capacity is the long term average value; strictly speaking it is a capacity estimate of any given configuration, because it is also changeable depending on demand, i.e., aircraft mix.

For a given set of weather conditions, several configurations are available to be used for operations, one of which will have the largest capacity. By using these maximum values, and correlating them with the percentage of time that these weather conditions are likely to exist, a "Capacity Coverage Curve" can be constructed. It describes the maximum hourly capacity available at the airport as the percentage of time during a year (although any period of time is acceptable).

Figure 13 shows the capacity coverage curve for Boston Logan Airport. In VFR weather, which exists at Boston during 40% of the year, the capacity is 126 operations per hour. Crosswinds then occur on various runways during another 40% of the year which make them unavailable for use and the hourly capacities continue to decrease. Some 2% of the year the airport is closed due to poor visibility, ceilings,

Figure 11.

TODAY'S VFR CAPACITY

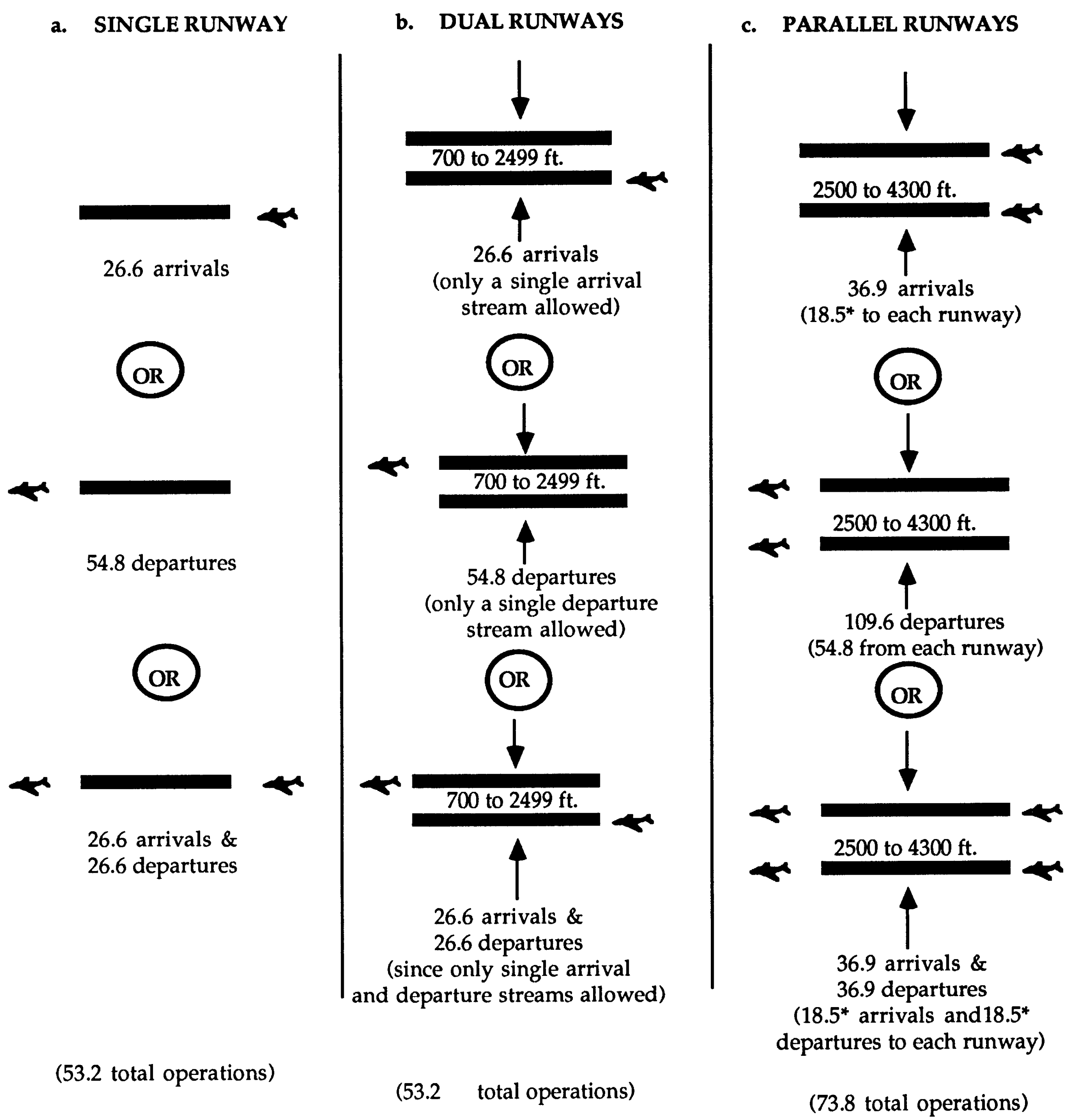


* Difference due to rounding

Source: MITRE MTR-87 W203

Figure 12.

TODAY'S IFR CAPACITY



* Difference due to rounding

Source: MITRE MTR-87 W203

TABLE 7·

COMPARISON OF TODAY'S VFR AND IFR AIRFIELD CAPACITIES

RUNWAY CONFIGURATION	TYPE OF OPERATION								
	Arrivals - Only			50% Arrivals, 50% Departures			Departures - Only		
	VFR (aircraft/hr)	IFR	Difference (percent)	VFR (aircraft/hr)	I FR	Difference (percent)	VFR (aircraft/hr)	IFR	Difference (percent)
Single	36.6	26.6	10.0 (-27%)	59.8	53.2	6.6 (-11%)	57.9	54.8	3.1 (-5%)
Dual	70.6	26.6	44.0 (-62%)	113.4	53.2	60.2 (-53%)	111.9	54.8	57.1 (-51%)
Dependent Parallel	73.2	36.9	36.3(-50%)	119.6	73.8	45.8 (-38%)	115.9	109.6	6.3 (-5%)

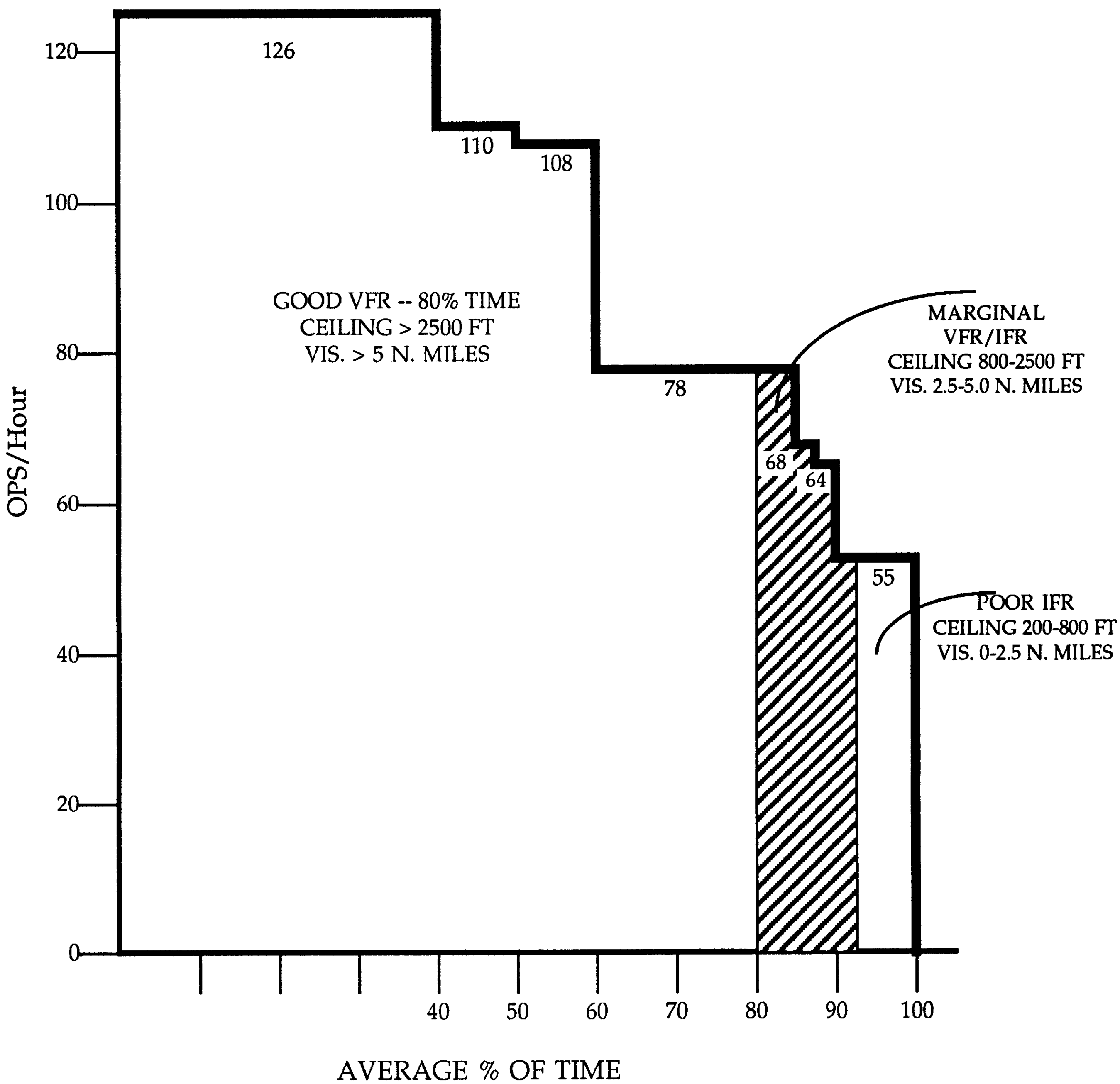
Source: MITRE MTR-87W203, October 1987.

FIGURE 13.

AIRPORT HOURLY CAPACITY VARIES STRONGLY WITH WEATHER

THERE IS A 3/1 OR 2/1 RATIO BETWEEN GOOD WEATHER/
BAD WEATHER CAPACITIES.

CAPACITY COVERAGE CURVE -- BOSTON LOGAN AIRPORT



SOURCE: Class Notes, MIT Course 16.781

and snow. There is a wide variation in hourly capacity from 126 to 55 operations per hour before the airport is closed. A smaller variation exists at airports which either have very good weather or a small number of runways; such a level capacity coverage curve means more predictable operations and allows schedules to be set which are more predictable, at least from the airside capacity supply point of view.

Improvements in ATC procedures or building new runways will raise the overall level of the capacity coverage curve, i.e., the maximum number of operations per hour will increase, but unless the weather itself can be managed, degradation of capacity with weather will continue to take place. Delays at major hubs where weather variations exist will continue to be inevitable unless traffic is scheduled to match bad weather capacities. This would not be sensible since it would result in an enormous reduction in usable capacity.

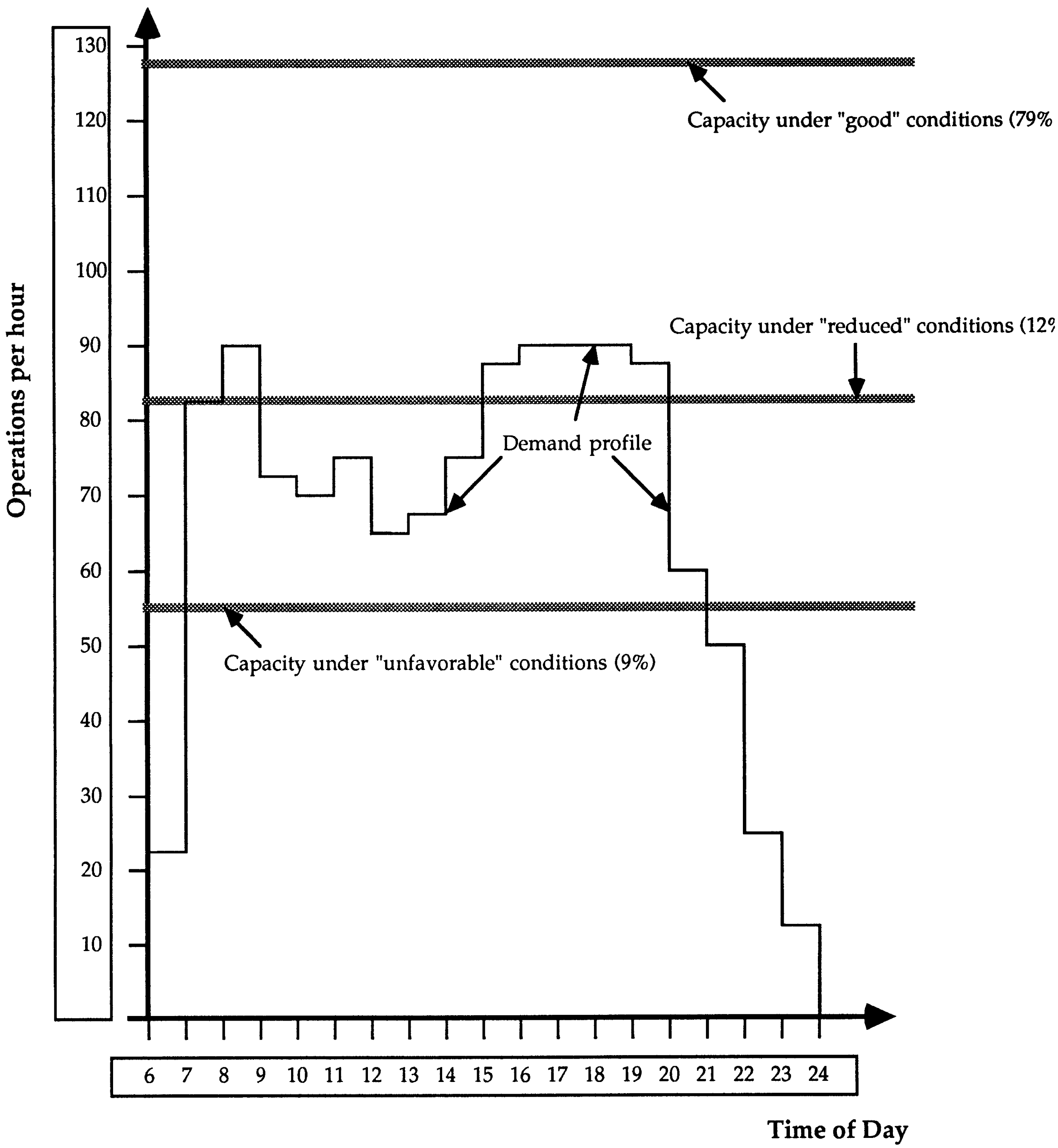
Logan Airport can accommodate daily demand comfortably under good conditions and almost all demand under reduced conditions. Only under "unfavorable" conditions does the airport become a problem (Figure 14). For major hubs like LaGuardia, O'Hare, Chicago or Atlanta where traffic is running near peak capacity conditions all day, almost any weather degradation will cause delays to start to mount (Figure 15).

Thus airlines (in the aggregate at an airport) must decide where the tradeoff exists between not using good weather capacity and the delays likely if scheduling is done in excess of bad weather capacity.

Even under good weather conditions the highest capacity configuration may not be in use if runways are chosen based on noise considerations. Normally this does not occur when traffic demand is high; on the other hand, when demand does not approach the available capacity of a number of configurations, the one with the highest capacity may not be the one chosen by the ATC controllers. If an airport chooses the lowest noise configuration available rather than the highest capacity available, as traffic builds up or as weather changes, additional changes occur which are not anticipated under the assumptions of the capacity coverage curve. Some trade-offs between environmental and capacity considerations may have to be made by the airport as a result of community pressures. A majority of all hub airports impose some operating restrictions based on noise, including curfews and maximum noise exposure rules (Figure 16). The large hubs with the greatest

FIGURE 14.

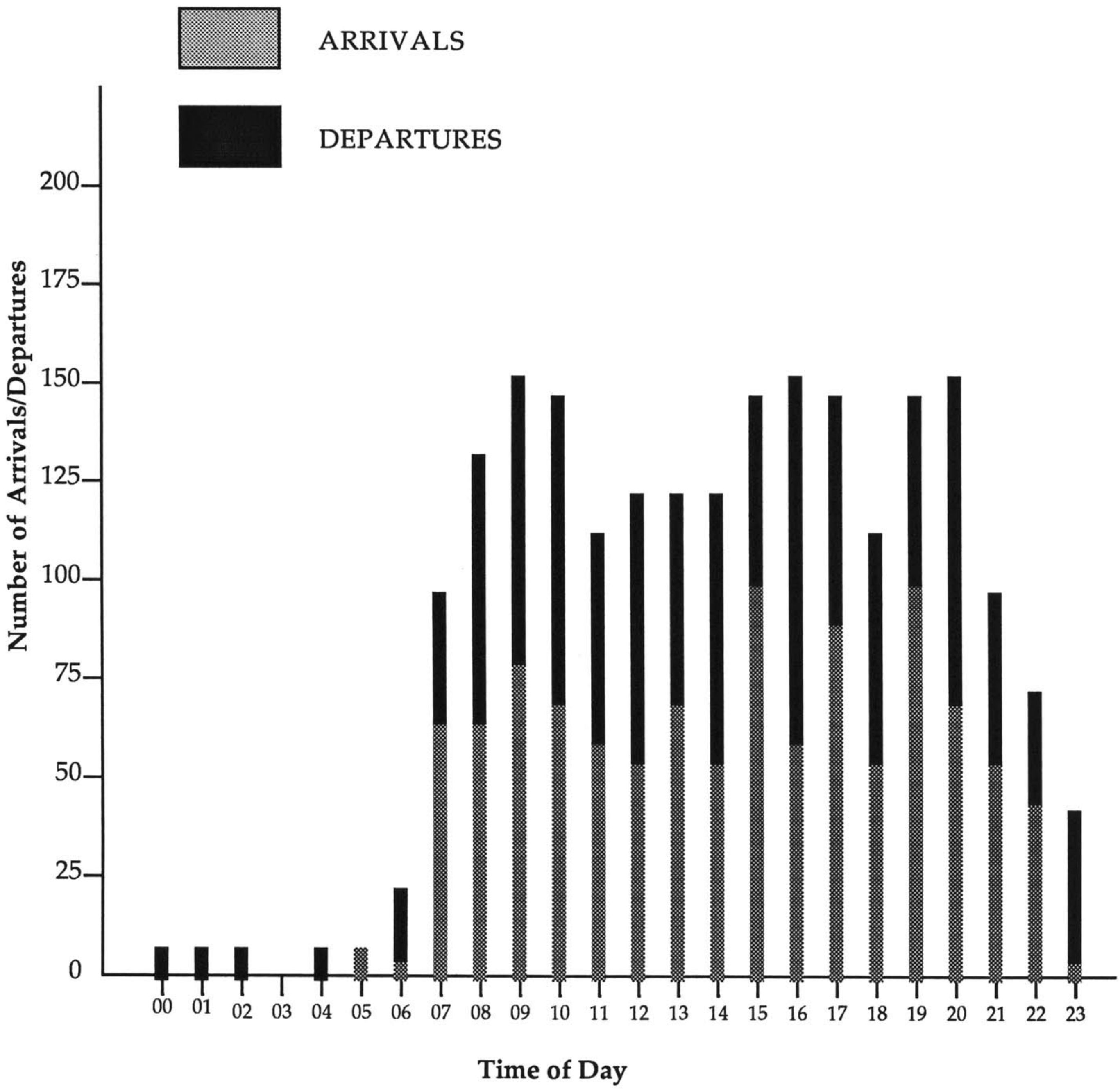
Demand vs. Capacity at Logan Airport (1987)



SOURCE: MIT Class Notes, 16.781

FIGURE 15.

Hourly Profile of Scheduled Arrivals and Departures
Atlanta International Airport



Source: Emily A. White, TRB Annual Meeting Session 46, 1991

Figure 16.
Noise Based Operating Restrictions At Hub Airports

OPERATING RESTRICTIONS:	% of HUB AIRPORTS:		
	LARGE (38)	*MEDIUM (37)*	*SMALL (61)*
CURFEWS	24%	8%	4%
USE RESTRICTION BY NOISE LEVEL	34%	8%	2%
OTHER OPERATING RESTRICTIONS	97%	84%	71%

Source: Emily A. White, TRB Annual Meeting Session 46, 1991.

amount of operations and the longest delays are also the points where the greatest impact of noise restrictions exist.

How much delay can be tolerated by the travelling public, the management of airlines, and the air traffic controllers? Anecdotal evidence indicates not much more. Charles Kuralt speaks for the public that flies a lot when he contemplates another hub in the making: "At friendly little old Raleigh-Durham ... American Airlines, which never even bothered to fly to Raleigh-Durham in the nice days, now deposits thousands of passengers there whether they want to be there or not, and after an hour or two, at its convenience, picks most of these same people up and flies them somewhere else. Raleigh and Durham are very proud that their airport is now a hub. So far, it's not a big enough hub to be notorious, but it's growing and may yet become nationally despised ... The country cheered when Ronald Reagan fired all those uppity air traffic controllers, and now -- how many years later? -- the captain is still on the intercom: 'Well, we're 13th in line to take off, folks.'"[1]

Airline managements are not happy either. Even though the numbers are imprecise, the cost of delays to the airlines was in the vicinity of one billion dollars in 1976, and has been climbing toward two billion (Figure 17), numbers in the same ball park as the best yearly profit of all airlines ($3b) in 1988. Cutting the cost of delays might even bring economic health to a staggering industry.

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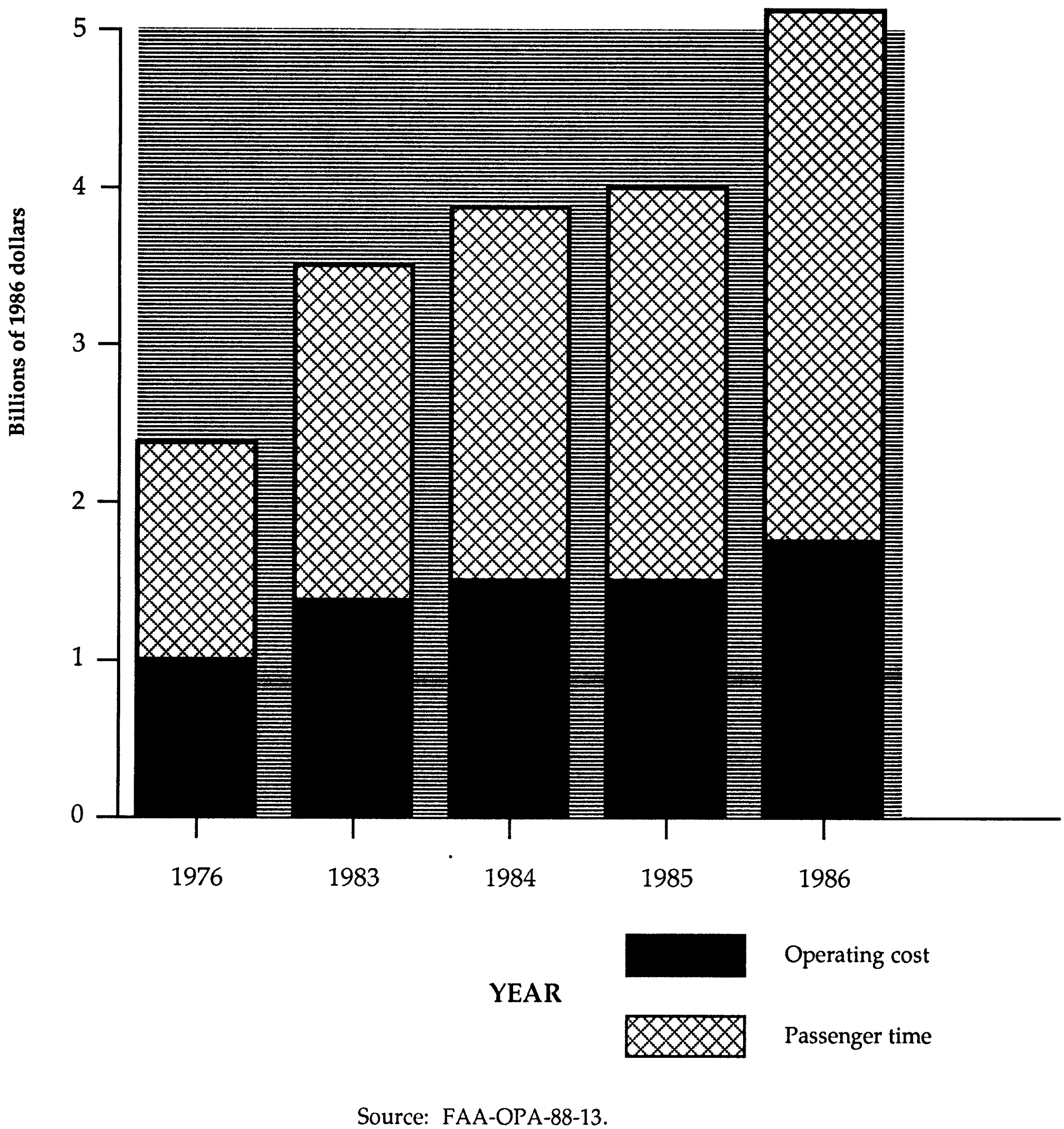
1 New York Times, October 14, 1990, p. 37.

FIGURE 17.

COST OF AIR CARRIER DELAY
(to air carriers and passengers)



Source: FAA-OPA-88-13.

3. Current Activities in Capacity Improvement

Since the FAA is generally responsive to the users of the airspace that is oversees, it has not been idle as traffic has been increasing in the last dozen years. New equipment has been installed at airports, runways or runway extensions have been funded, and plans exist for further major infrastructure upgrades. The latest (1991) version is the "Aviation System Capital Investment Plan." While capacity is a key element of any future plans, at the same time the FAA must overcome the day-to-day delay problems. Certainly improvements in the Central Flow Control System have helped to keep down airborne delay, albeit at a cost in increased ground delay.

Until the terminal air traffic control automation (TATCA) and automated en route ATC (AERA) projects, as well as the on-again, off-again MLS, are completed, the FAA is working on runway oriented procedural improvements that could increase runway capacities. The intent of these improvements is to bring IFR capacity closer to VFR capacity, and at some airports IFR operations could approach VFR operations. However, on an annual basis the improvements in capacity may not be that impressive since IFR conditions only exist for a small portion of the year.

These methods are summarized in Table 8. Almost all of the top 100 airports will have some improvement if and when those procedures are implemented. Additionally there are FAA sponsored projects for airfield and facility improvements at various airports throughout the US, although prospects for runway construction at the most critical airports are not promising because of noise-fed community opposition to expansion. There may be less opposition at newly established hubs (such as Raleigh, Charlotte, etc.) where the community is, at least for now, happy to get the extra benefits of increased service. Figure 18 shows some potential new hubs that have been identified by the FAA.

Thus noise is not only the key to new airport construction, but also to improvements at existing airports. Stage 3 is not going to be the answer; for example, Figure 19 shows that the expected impact of elimination of Stage 2 aircraft by the year 2000 at Newark will be minimal. Those communities around Newark which were noise free until the FAA's Expanded East Coast Plan (and its revisions) came along are now particularly vociferous, as are all communities which suddenly

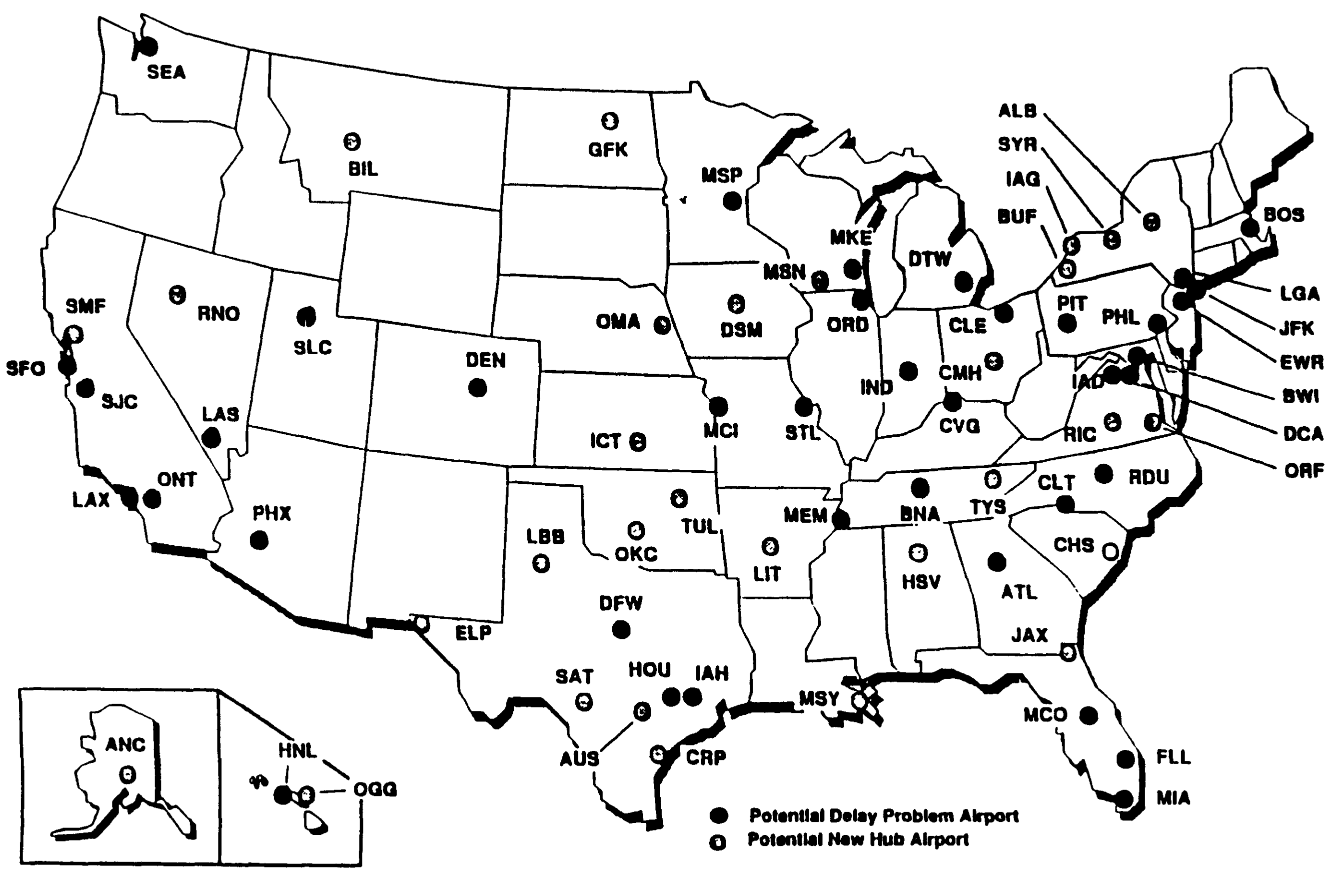
TABLE 8. METHODS TO INCREASE CAPACITY AT EXISTING AIRPORTS

Method	Description	Application
Dependent parallel IFR approaches	Existing rules require that the separation between parallel runways be at least 2,500 ft for dependent IFR operations with 2.0 nautical miles (nmi) diagonal separation between landing aircraft. Recent studies show that this diagonal separation could be safely changed to 1.5 nmi.	27 of the top 100 airports have or plan to have parallel runways with spacing of 1,000 to 2,499 feet and are candidates for dependent parallel IFR approaches.
Independent parallel IFR approaches	Separation between parallel runways must be at least 4,300 ft for simultaneous independent IFR operations. The FAA is actively pursuing ways to change this separation standard to a goal of between 2,500 and 3,000 ft. This may permit an increase of 12 to 17 operations per hour under IFR.	Among the top 100 airports, 28 have or plan to have parallel runways with spacings between 3,000 and 4,299 ft.
Dependent converging IFR approaches	The objective is to lower the runway visibility minima for approaches to converging runways. Preliminary studies indicate that dependent approaches to converging runways can be safely conducted in ceilings down to Category 1 Minimum Decision Height (200 ft.).	Among the top 100 airports, 58 are candidates for dependent converging approaches.
Independent converging IFR approaches	Under VFR it is common to use nonintersecting converging runways for independent streams of arriving aircraft. In IFR this practice is restricted to decision heights above 200 ft. Development of new procedures to ensure safety in the event of simultaneous missed approaches would allow independent converging IFR approaches down to Category 1 Minimum Decision Height (200 ft)	Among the top 100 airports, 33 are candidates for independent converging IFR approaches.
Triple IFR approaches	If IFR approaches to triple runways (using either the current 4,300-ft lateral separation standard or the proposed 3,000-ft standard) were permitted, airports could achieve up to a 50 percent increase in IFR arrival capacity.	Among the top 100 airports, 10 are candidates for triple IFR approaches.

Source: Airport System Capacity, TRB, 1990

FIGURE 18.

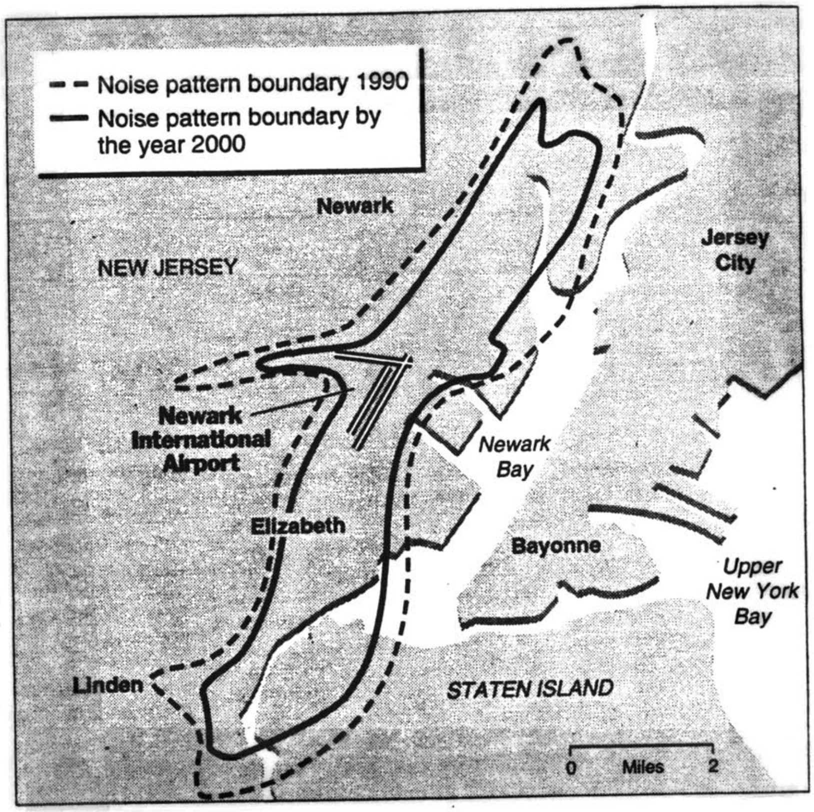
POTENTIAL NEW CONNECTING HUB AIRPORTS



Potential New Connecting Hub Airports Having Dual IFR Approaches
(More Than 50 Miles from 1998 Potential Delay Problem Airports)

SOURCE: 1990 - 91 FAA Aviation System Capacity Plan

FIGURE 19



SOURCE: New York Times, Sept. 26, 1991, p. C-2 become impacted by noise when the FAA tries to change flight paths and spread noise around more evenly. It is a no-win proposition and routes may become established on a least-complaint basis. In order to placate its communities, the Port Authority of New York and New Jersey is planning to issue stricter rules on Stage 2 aircraft to the airlines serving its airports and thus superseding the FAA's new noise rules. The FAA will undoubtedly contest the Port Authority in court.

There are a number of problems that have to be addressed in the noise area, aside from the level of noise (dB) itself. One issue is the method of determining the noise footprint area, which uses an average noise level over a twenty-four hour period (DNL 65dB). ("If a stick of dynamite blew up once a day outside my front door, it would be nonexistent, according to the way the FAA does things."[1])

The DNL 65dB also makes no distinction as to the type of area being overflown, i.e., urban areas, which have a lot of ambient noise, and rural areas, which are generally noise free, are assumed to be similarly impacted. And if more operations of Stage 3 aircraft are scheduled because they theoretically produce the same footprint as those of fewer Stage 2 aircraft, people will be fully aware of this, since annoyance is not just related to the level of noise but also to the frequency of flights. Clearly the current footprint definitions do not impress the airport neighborhoods. It will not do for the FAA to simply declare that communities are not experiencing "significant aircraft noise" because they are outside some arbitrary noise footprint defined by inadequate measures.

"Noise is the major issue in airport expansion," says Kenneth Feith, a senior scientist and noise specialist with the EPA. "As it is, airports have to conform to thirty-seven categories of noise 'procedures,' including state and local noise ordinances, restrictions against specific aircraft types, weight limitations, thrust requirements, and night-time curfews."[2]

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1 "The New Yorker", October 21, 1991, p. 32.

2 "Cut Out That Racket", Atlantic Monthly, November 1991, p. 54.

Even when alternative transportation systems are discussed as an answer to the capacity problem, noise still remains an overriding issue. A variety of vertical and short takeoff and landing (V/STOL) concepts have been touted since the 1960s as the solution to the crowded sky.

Of the V/STOL family, the only successful VTOL aircraft has been the helicopter, which unfortunately has operating costs which are about three times higher than a similarly sized turboprop aircraft. Few helicopter airlines have been profitable, even with subsidies from governments or airlines. Thus the tiltrotor concept came about as an attempt to merge vertical and level flight. The tiltrotor is an aircraft which has a pivoting engine and rotor combination mounted on each wingtip, operates like a helicopter when the rotors are vertical (powered lift) and like an airplane when the rotors are horizontal (wing lift). The basic advantages of a tiltrotor over a helicopter are increased speed and range. The economics of the tiltrotor are still unknown, although they are likely to be more similar to a helicopter's than a turboprop's due to the additional complexities -- vertical lift, which eliminates the need for runways, does not come cheap. Some of the additional capabilities that this extra cost buys are: automatic hands-off, stabilized hover in gusty winds; automatic steep, decelerating descents; speeds up to 300 mph cruising at altitudes between ten and twenty thousand feet with a 300-500 nm range; and cross-shafting, automatic reserve thrust for single engine failures.

Tiltrotor technology has a long history. In the 1950's NACA and the military supported research on advanced helicopters, compound helicopters, tilt wings, tilt rotors and direct jet lift. In the 1960's V/STOL studies continued for both civil and military applications. In the 1970's NASA, with DOD support, built a tiltrotor prototype, the XV-15, and flight test demonstrations began in 1977. In 1983 the DOD (Navy) awarded the JVX contract to Bell and Boeing, followed by a full scale development contract for the V-22 in 1986 with an order for six prototypes. The first flight of the V-22 (with transition from helicopter to airplane) took place in March 1989. In the meantime, research on advanced tiltrotor concepts continues, such as Sikorsky's variable diameter (telescoping) rotors to achieve greater efficiency in the airplane mode.

In 1970 a three year long investigation by the old Civil Aeronautics Board (CAB) into the need and feasibility for V/STOL service in the Northeast Corridor concluded that "... it is essential that V/STOL operations be segregated from CTOL (conventional) from the outset." But despite the advocacy of the CAB no scheduled V/STOL operations resulted from the Northeast Corridor study, nor from many others, the latest of which was the civil tiltrotor (CTR) study finished in early 1991 by Boeing. Just as in all the previous studies, it found a need for a vertiport in New York City and the other major cities in the Northeast. However, cities apparently do not believe in the maxim "If you build it, it will come," since no vertiport network has been established.

In 1970 the risk for the airlines was " ... buying a new aircraft technology to operate into a facility that is not yet built to serve an unknown level of traffic at a yet to be determined fare."[1] Since then airline traffic has almost doubled, so the Boeing study forecasts a need for 1,200 CTR aircraft by the year 2000 in North America alone (Figure 20); even under 1989 traffic conditions some 1,000 departure slots could be diverted from the major Northeast airports if a tiltrotor network existed. Such a potential reduction of air traffic delays argues strongly for tiltrotor technology. Table 9 summarizes CTR system issues. However,

> "Tiltrotor aircraft, which will cost more to purchase and operate than conventional airplanes and will require new infrastructure, turn few heads in airline management. Before an airline will consider placing orders for a commercial tiltrotor, it must be convinced that the aircraft is operationally reliable and economically viable."[2]

While the FAA must necessarily take the major initiatives toward improving capacity, there is a wealth of technical talent available at other civilian agencies of the U.S. government to help in their efforts, as well as the Defense Department. For example, the Next-Generation Weather Radar (NEXRAD), a long range Doppler radar system, now being installed and known as WSR-88D, was a tri-agency development of Commerce (NOAA-NWS), Transportation (FAA), and Defense

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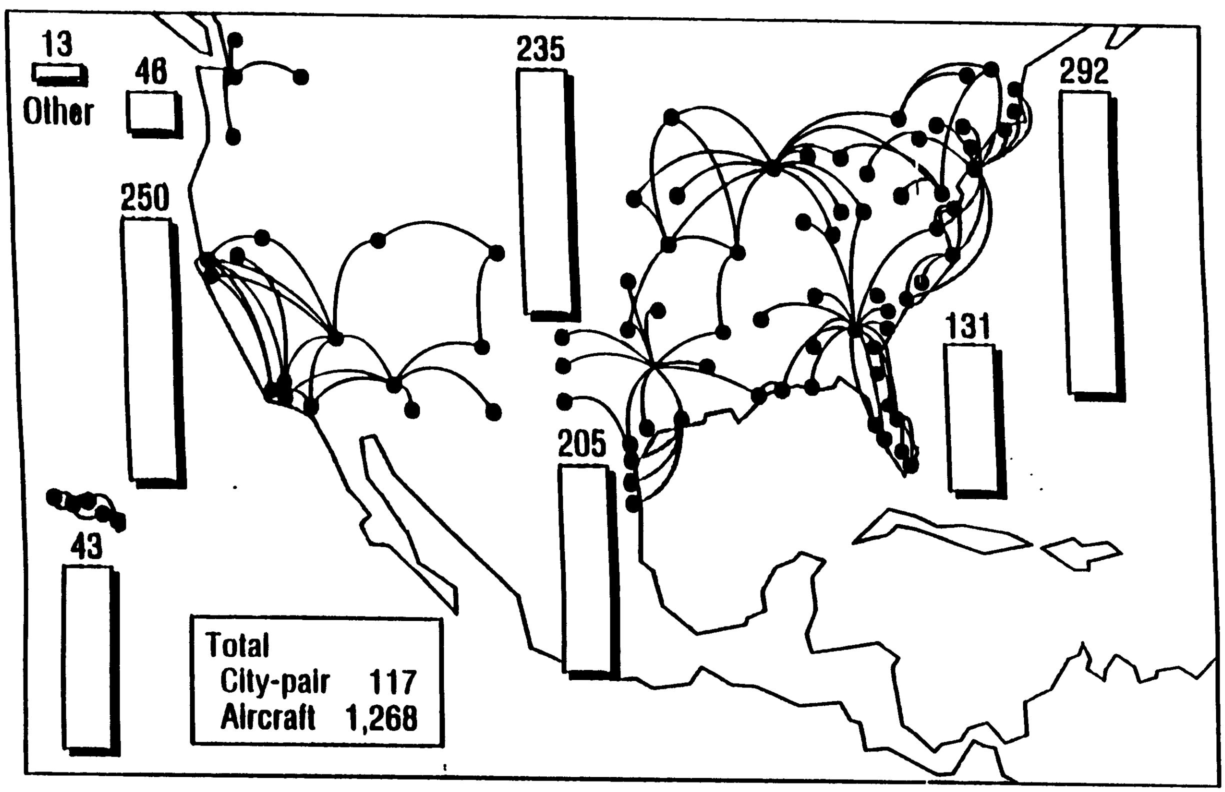
1 "Space / Aeronautics", May 1970, p. 31.

2 U.S. Congress, Office of Technology Assessment, New Ways: Tiltrotor Aircraft and Magnetically Levitated Vehicles, OTA-SET-507, October 1991, p. 53.

FIGURE 20.

NORTH AMERICA: CTR PROJECTED SYSTEM IN THE YEAR 2000 (PASSENGER)



SOURCE: Boeing, NASA CR 177576, Feb. 1991

TABLE 9
TILTROTOR SYSTEM ISSUES

Component	Issues	Comments
Tiltrotor aircraft	V-22 program status; need for a civil demonstration program; commercial market size.	Administration has attempted to end the V-22 in fiscal years 1990 and 1991; civil demonstration program proposed in the NASA/FAA Phase II study.
Vertiport	Federal airport capital grant policy for vertiports is unclear; sites that are acceptable to communities and are operationally suitable depend in part on new technologies and flight procedures.	Waterfront, industrial, underused small airports, and nonurban interstate sites appear plausible; residential and central business district locations doubtful; multiple-use facilities could help limit development costs for vertiport portion.
ATC system	Appropriate technology, procedures, and manpower needed to gain benefits of tiltrotor flight capabilities. Large increase in the number of daily en route flights possible.	Rotorcraft have never been well integrated into the airspace system; no public heliport in the United States now has precision instrument landing capabilities essential for scheduled passenger operations. En route operations by tiltrotors are no different than those by conventional aircraft, and FAA has programs under way to enhance the capabilities of en route airspace.
Regulatory oversight	Cockpit design and pilot training; noise standards for tiltrotor and vertiports.	V-22 flight test data are being analyzed by FAA; airworthiness criteria for tiltrotor-type aircraft are published (in interim form); vertiport planning guidelines are available; airspace procedures are being studied in simulators.
Potential operators	Major airlines have not embraced tiltrotor. Are potential tiltrotor system benefits realizable for an existing or entrepreneur airline?	Lack of aircraft and infrastructure has dampened airline interest; airlines will not voluntarily free up airport capacity for competitors; scheduled passenger helicopter service, in some respects comparable to tiltrotor, is virtually nonexistant in the United States.
Local communities	Noise, safety of overflights, and potential increases in surface traffic are key community concerns.	With appropriate airspace procedures, vertiports and their operations could be isolated from residential areas; some planning analyses are under way (e.g., FAA vertiport studies).
Passengers	Would potential passengers recognize cost and service benefits of tiltrotors?	Safety and service levels at least comparable to large commuter operations required; total direct ground and air costs to passengers could be less than current air options in certain markets. How do travelers value ground access time and cost?
Financiers and investors	What assurances are needed for non-Federal investors in tiltrotor technology and what is the Federal role?	Public and private investment in the United States limited primarily to planning and design studies to date; new heliports are being designed to vertiport standards; no commitment to develop commercial tiltrotor in the United States.

Source: U.S. Congress, OTA, New Ways, OTA-SET-507, October 1991, p. 51

(Navy Oceanography and AF Air Weather). Also available in the weather area is the National Center of Atmospheric Research (NCAR) which has been working with the FAA on advanced aviation weather sensing and processing technology, There were plans in 1991 for FAA, NOAA, and NASA to work together on a revitalized wake vortex research program to reduce terminal area separation standards which appears to have been abandoned. Such a program should proceed as rapidly as possible since in the near term improved separation procedures, rather than facility buildups, are the best hope for increased capacity, and wake vortex research falls squarely into the type of research where governmental agencies can pool their many talents for a potentially high payoff. Wake vortex alleviation was predicted to result in airport capacity increases in the 10-15 percent range. There are many other FAA/NASA cooperative programs in such areas as laminar flow, MLS procedures, airborne windshear detection, TATCA, and airport-aircraft compatibility (ROT and airport pavement). (The FAA Plan for RE&D [January 1989] or FAA 1990-91 Aviation System Capacity Plan have detailed descriptions of the projects.)

The aviation community, working together, must establish a data base system which can be used to estimate and forecast capacity and delay: clearly even a set of agreed upon definitions of the basic terms would be a major accomplishment. Without agreed upon definitions, such often quoted statements as "A one percent gain in capacity results in a five percent reduction in the cost of delays" are generally meaningless. Since working with the existing data bases can lead to erroneous or contradictory conclusions, it is essential to establish such a uniform system to accurately determine the amount of delay in the US air transportation system. This will, at least tangentially, indicate the state of overall capacity in the system. It is particularly important to have an accurate system to be able to establish trends for estimates of future developments.

4. Recommendations for NASA Research Activities

4.1 Airport Community Noise

Since the airport community noise problem is recognized as the fundamental, long term cause of the lack airport capacity in the U.S., and the world's, air transport system, noise research activities are of vital importance. The goals for such research should be:

(a) Quietening aircraft noise at its source

(b) Moderating airport community annoyance

(c) Separating aircraft from the airport community

(a) Aircraft Noise

Research in this area should consider engine, airframe, rotor and fan noise. Current transport vehicles (propeller aircraft and subsonic jets), as well as more advanced vehicles such as high speed civil transports (HSCT) and civil tiltrotors (CTR) should be included. Techniques for active suppression for fan engine noise and other novel noise suppression techniques for propellor and rotor noise should be further explored.

There is also a need to establish reasonable noise goals for further quietening of new transport aircraft on a worldwide basis (i.e., Stage 4, Stage 5) since it is clear that the achievement of all Stage 3 operations is not going to alleviate community objections to airport noise.

(b) Moderating Annoyance

Research in this area should focus on psycho-acoustic responses of airport communities to short-term and long-term noise exposure for varying event noise levels and event frequency of occurrence. This should encompass long-term, continuing field and laboratory work to gauge the psychological response of airport listeners under a variety of circumstances; (e.g., after one, or two, or three hours of continuous exposure, with different living or working conditions, after several years of such airport exposure, etc.). The short term transient response is needed to guide the introduction of noise relief by rotating the runways at a major airport every few hours when possible.

Additionally, the tradeoff of peak overflight noise and number or frequency of exposure events is still not well established. It is needed to understand future problems as the daily number of flights at an airport continues to increase when peak noise levels decrease as Stage 3 aircraft continue to enter the fleets of the U.S. airlines. The current airport community noise measures, developed 20 years ago when aircraft overflight noises were much more severe, are clearly inadequate as a measurement in future situations.

(c) Separating Aircraft

Research is needed on methods of operating vehicles on various trajectories for takeoff and landing to minimize exposure to noise from a single overflight on the community.

With the advent of advanced flight control and guidance systems, it is possible to consider flying complex trajectories for takeoff and landing which avoid placing peak noise levels on the airport community.

One such path is a parabolic, constant deceleration approach path where the aircraft decelerates horizontally at a constant rate while maintaining a fixed vertical rate of descent. With microwave landing systems and flight management systems (FMS) it would seem possible to safely fly such trajectories which offer higher altitudes and lower power (and therefore lower noise impact). It is particularly appropriate for helicopters and tiltrotors operating in city center areas, where for both noise and fuel reasons it is desirable to minimize the time spent at hover or steep approach.

Finally, since the noise generating from any aircraft is not equally strong in all directions, there can be advantages in flying a safe takeoff path which manages to keep the aircraft from orienting its strongest noise at underlying communities. The overall effectiveness of such techniques depends on the distribution of population around an airport and its runways. Noise minimization profiles would be required for each runway, gross weight, wind condition, etc., but could be generated by, or stored in the FMS of modern transport aircraft.

4.2 *Civil Tiltrotor Vertiport System*

To divert the short haul business air traveller from conventional air transport aircraft and airports, it is necessary to demonstrate that a safe, economically viable, and environmentally acceptable system of vertiports can be built. Research must be concentrated in the following areas:

(a) CTR Noise Research to Allow Community Acceptance

(b) Precision Flight Paths for CTRs

(c) Improved CTR Technology

(a) CTR - Community Noise Research

Although vertiports would theoretically be located in urban areas where there is a high level of ambient noise, very frequent helicopter flights over cities have proven objectionable. Research is needed on CTR approach and departure noise patterns during vertiport operations and on community reaction to these CTR operations. Flight demonstrations will be a necessary part of this process.

(b) CTR Precision Flight Paths

In conjunction with studies on noise patterns, research is needed on precision guidance for decelerating approach transitions that will minimize noise. Also required are studies on wake effects from simultaneous operations at vertiports.

(c) Improved CTR Technologies

This topic requires research to achieve lower operating costs and improved operational reliability of the vehicle, including improved rotor performance and reduced noise. To overcome some of the hesitation of potential airline clients, research is also needed to evaluate acquisition and operational costs of CTR systems.

4.3 *Precision Flight Path Capability*

Increasing capacity in the air traffic control system requires reducing the separation criteria used for safe separation. Current ATC systems impose large separations between aircraft in non-visual conditions because it has not been possible to specify and then fly precisely defined paths in two, three, and four dimensions. In order to increase capacity in the ATC system, it will be necessary to introduce precision flight path capability. To achieve this capability, there is no need to invent new technologies, but there is a need to demonstrate and apply existing technologies. These technologies are in the following areas:

1. Aircraft Navigation (2-D, 3-D, 4-D)

2. Aircraft Guidance

3. Surveillance of Aircraft and Weather

4. Air/Ground Data Communications.

To demonstrate that the technologies for precision flight path capability are ready for use in the ATC systems, the following topics require further research.

(a) Monitoring & Intervention of Abnormal Divergences

Improved methods of monitoring cross-track velocity are needed for aircraft which suddenly diverge from the runway centerline (e.g., downlink heading, turn rate, or bank angle). In general, there is a need for improved ground surveillance and "intelligent" tracking of aircraft which uses information on current aircraft state to avoid transient errors in estimating groundspeed and direction when aircraft are maneuvering. This requires downlinking of aircraft state information.

Improved methods to determine and communicate a safe escape maneuver for the non-diverging aircraft on the other approach path are needed. At the same time, a safe recovery maneuver for the diverging aircraft is being established. While TCAS will be available, its transient response is poor, and there is a need for an improved cockpit display of relative position and speed, and short term intended path. This information can be displayed on the basic horizontal situation display used for approach.

(b) Precision Guidance in the Departure Area

Better methods are needed to define and fly precision paths in the area beyond the runway to ensure safety in the event of single or multiple simultaneous missed approaches, and in the event of contingency departures (i.e., an engine failure or other emergency).

These paths are complex, may start from various points, may include turns and climbs, and may be performed with a single engine failure or other emergency. Aircraft performance to ensure obstacle clearance is critical.

Paths could be tailored to each runway, its obstacles, current air traffic operations, aircraft gross weight, winds, temperature, etc. Modern FMS can select best paths and present it to the pilots and controllers.

By defining them, tighter, higher capacity terminal area ATC procedures can be operated safely.

(c) Deviation Detection, Oceanic Parallel Track Systems

Currently there is no monitoring and intervention system for Oceanic ATC since surveillance and communication are inadequate. Track systems with 60nm lateral spacing are defined each day to optimize travel time and organize traffic flow on certain routes.

While the lateral conformance of aircraft in the traffic mix keeps improving and the GPS system promises further improvements, the safety criteria for track spacing become dominated by the rare occurrences of abnormal deviations.

To reduce to 30 nm. lateral spacings, it will be necessary to develop some method of detecting abnormal lateral deviations due to failures by humans or equipment.

(d) Hybrid Navigation Management Systems

It is likely that the aviation world will begin using multiple systems to obtain navigation information in the future rather than a single world system. ICAO is establishing RNP (Required Navigation Performance), which is a classification system describing the navigation (and guidance capability) of each aircraft. ATC rules and procedures would then be based on this classification system.

There is a need for research to establish a basis for describing the performance of hybrid navigation systems which use multiple sensors (GPS, Glonass, Loran-C, Omega, Inertial, Multiple DME, etc.). It is needed for certification of various hybrid forms of aircraft Navigation Management Systems, for setting a basis for RNP, and for examining how a reliable, real time, cockpit indication of navigation accuracy can be developed for any combination of sensors.

(e) Trajectory Prediction for Climbing/Descending Aircraft

Current ATC practice does not require aircraft conformance to either 3-D or 4-D paths. There would be significant improvement in traffic handling capacity around busy airports if climb/descent trajectories for subsonic transports could be predicted with better accuracy. Currently little knowledge is obtained about the winds and temperatures which vary along the flight paths over short periods of 5-20 minutes.

Climb performance depends on current gross weight, speed and engine thrust profiles used, and the actual performance of engines. There can be significant variation within a fleet of supposedly identical aircraft.

Descent performance can be made independent of aircraft type or engine performance by specifying a "Constant Profile Descent" where aircraft fly a specified constant Mach/IAS and rate of descent.

There is a research need to determine how accurately the Climb and Descent trajectories of transport jet aircraft can be predicted 5-20 minutes ahead given good forecasts of winds/temperatures and surveillance of their current performance. There is also the issue of defining a 3-D path and requiring conformance to it using advanced FMS.

(f) Airborne Wake Vortex Detection on Final Approach

The possible persistence of strong wake vortices behind heavy aircraft at low speed on final approach has introduced extra longitudinal separations between aircraft even though they are not needed on most days. It has been observed that longer persistence occurs only under certain weather conditions (low wind speeds and a stable atmosphere).

It is operationally desirable for the pilots to be able to detect the location and strength of the wake vortices from a preceding aircraft at distances of 1-5 nm. If possible, their relative height is also needed.

For the case of converging or crossing runway operations in poor visibility, it is also desirable to be able to detect a crossing vortex in front of an aircraft.

(g) Reduction of Separations in Final Approach Area

Currently, a radar separation of 3 nm. applies under every situation in the final area except after the Outer Marker of an ILS precision approach where it is relaxed to 2.5 nm. as aircraft reduce from a maneuvering speed of 170 kts. IAS to their approach speeds (around 140 kts.)

For certain situations such as merging a slower aircraft behind a faster, and for aircraft established "in-trail" at similar speeds, it is clear that 3 nm. could be safely reduced. With newer automation systems which provide reliable assistance to the final spacing controller such as the Final Approach Spacing Tool (FAST) in the Center/Tracon Automation System (CTAS) developed by NASA Ames, the issue of tightening these separation criteria arises. It is desirable to switch to time based separation criteria for higher capacity landing rates.

With advanced FMS in aircraft and a reliable air-ground datalink, it will be possible to issue "digital vectors" for complex 3-D or 4-D paths to be flown with good conformance.

There is need to develop a methodology which defines safe time-based separations for merging and final spacing in a much more comprehensive way for such advanced scenarios. It should be dependent on the expected conformance capabilities of each aircraft.

(h) Air-Ground Integrated Voice/Digital Communication

There are Human Factors problems for both the pilots and controllers in introducing a second mode of air-ground communications called "digital vectors" as postulated in (g). A second area of research must be undertaken if higher landing and takeoff capacities are to be achieved.

In the automated terminal environments foreseen by CTAS, research is needed to understand the implications on safety and workload of the various alternatives for integrating voice and digital messages in a busy terminal area.

4.4 *Study Conclusions*

Community reactions to noise around airports and vertiports 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. Noise research is needed to understand community long-term and transient annoyance to quieter operations.

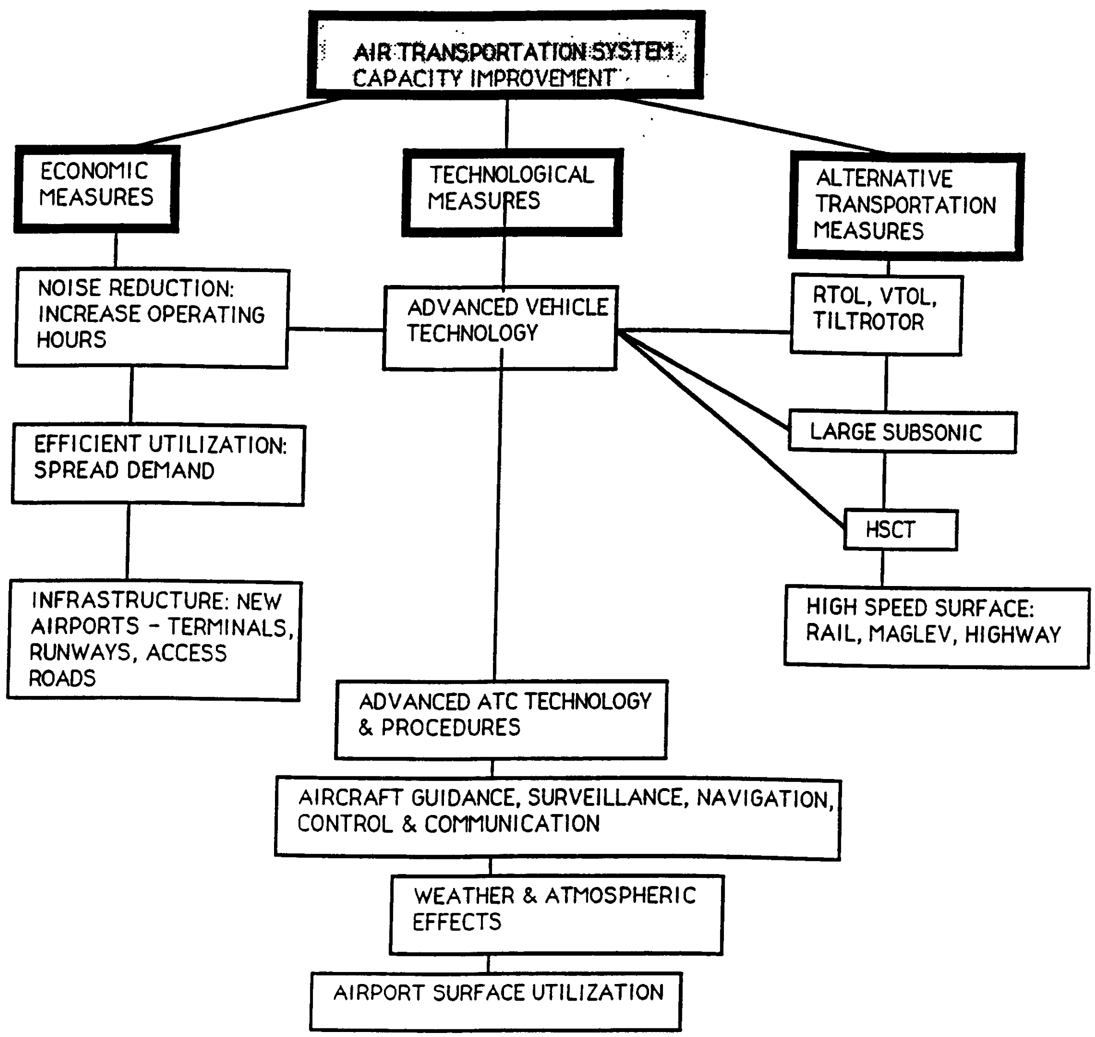
There are valuable returns from exploiting existing technology to reduce current ATC separation criteria used in Oceanic and Terminal areas. To demonstrate safe reductions, it is necessary to introduce the capability for Precision Flight along 3-D and 4-D paths to a majority of aircraft in the traffic flow.

There is a need to provide evidence of the economic, environmental, and operational viability of a CTR Short Haul Air Transport System to support decisions by federal and local government, and the aviation industry to embark on a long-term CTR development program.

Finally, an overview of alternative measures that can be taken to improve the capacity of the air transportation system is shown in Figure 21. This report has focused on noise research, ATC and aircraft technology measures, and civil tiltrotors, all items which are coupled through advanced vehicle technology. Since NASA, or at least the aeronautics part of NASA, has principal responsibility to foster technological development of air transport vehicles, it is in this role that it is fitting for NASA to commit resources to improving capacity of the U.S. airspace system.

FIGURE 21:

OVERVIEW OF CAPACITY IMPROVEMENT



Selected Bibliography

"Aeronautics Technology Possibilities for 2000", National Research Council, 1984.

"Airport System Development", OTA, 1984.

"Report on Airports and Airways",National Council on Public Works Improvement, 1987.

"Civil Tiltrotor Missions and Applications: Summary Final Report", Boeing [NASA CR 177452], 1987.

"National Plan of Integrated Airport Systems", FAA, 1987.

Safe Skies for Tomorrow", OTA, 1988.

"New Technology and the Aviation System", University of California at Berkeley [ITS-P-89-1], 1989.

"A Basis for Research and Development Planning for Civil Aviation in the 21st Century", AIAA, 1989.

"Air Traffic Control Environment in 2010", TSC, 1989.

"Future Aviation Activities", TRB, 1989.

"Secretary's Task Force on Competition in the U.S. Domestic Airline Industry", DOT, 1990.

"1990-1991 Aviation System Capacity Plan", DOT/FAA, 1990.

"Aviation System Capital Investment Plan", FAA, 1990.

"Airport System Capacity: Strategic Choices", TRB, 1990.

"Civil Tiltrotor Missions and Applications, Phase 2: The Commercial Passenger Market", Boeing [NASA CR 177576], 1991

"New Ways: Tiltrotor Aircraft and Magnetically Levitated Vehicles", OTA, 1991.

Acronyms

ADS	Automatic Dependent Surveillance
AERA	Automated En Route Air Traffic Control
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATOMS	Air Traffic Operations Management System
CAB	Civil Aeronautics Board
CTOL	Conventional Takeoff and Landing
CTR	Civil Tiltrotor
DME	Distance Measuring Equipment
DOD	Department of Defense
DOT	Department of Transportation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FMS	Flight Management System
FSS	Flight Service Station
GA	General Aviation
GNP	Gross National Product
GPS	Global Positioning System
HSCT	High Speed Civil Transport
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
MAGLEV	Magnetic Levitation
MLS	Microwave Landing System
NACA	National Advisory Committee for Aeronautics
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAR	National Center of Atmospheric Research
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
PFC	Passenger Facility Charge
RE&D	Research, Engineering and Development
RNP	Required Navigation Performance
RTOL	Reduced Takeoff and Landing
SDRS	Standardized Delay Reporting System
TATCA	Terminal Air Traffic Control Automation
TCAS	Traffic Alert and Collision Avoidance System
VFR	Visual Flight Rules
V/STOL	Vertical/Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing